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Theoretical and Experimental Aspects of Ring Currents

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ABSTRACT

Various geophysical phenomena have led to the speculation that a toroidal ring current encircles the Earth. Presumably, this current causes a magnetic field which is observed at the Earth's surface during magnetic storms and which influences the motion of charged particles moving in the vicinity of the Earth. Recent theoretical developments appear to explain how such a current originates and is maintained. The modern theory of ring currents is described in terms of its historical development. Early ring current theories due to Stoermer, Chapman and Ferraro, and Alfvén are discussed and contrasted with the recent work of Singer and Dessler and Parker. Rockets and space probes are providing the first opportunity to investigate the existence of the ring current by direct field and particle measurement above the ionosphere. The empirical results obtained by *Pioneer 1*, *Lunik 1* and *2*, *Explorer 6*, *Vanguard 3*, *Pioneer 5*, and *Explorer 10* are reviewed.

I. INTRODUCTION

Throughout most of this century there has been a persistent scientific interest in the possible existence of a geomagnetic ring current. The ring current is a toroidal current concentric with the Earth and lying in the equatorial plane. The ring current is expected to be a westward current of several million amperes. It is typically placed at a geocentric altitude of 5 to 10 R_E (R_E = Earth radii), i.e., in the tenuous outer fringes of the Earth's atmosphere. A ring current is a convenient source of a large-scale, quasi-uniform magnetic field. The existence of such a field surrounding the Earth may account for certain geophysical phenomena associated with magnetic storms and aurorae.

The ring current is one of a class of large-scale currents which deform or perturb the geomagnetic field. Presently accepted theories, which are supported by the available experimental evidence, suggest that the Earth's field is confined to a cavity inside the interplanetary medium (see Ref. 1 and 2). The cavity contains the geomagnetic field and the ionized outer atmosphere of the Earth, including the Van Allen radiation zones. The magnetic energy inside the cavity exceeds the kinetic energies of the plasma (ionized gas) and the trapped, high-energy particles. For this reason, the cavity is called "the magnetosphere." The boundary, or "magnetopause," consists of the compressed geomagnetic field on one side and the perfectly conducting, interplanetary gas on the other. The containment of the geomagnetic field implies that currents flow along the inner surface of the cavity. Thus there is a large-scale current system at the termination of the geomagnetic field. The best estimates, based on data from space probes, place these currents at 15 R_E on the side of the Earth facing the Sun. The interplanetary plasma is not stationary, but it is flowing outward from the Sun. This streaming gas is frequently referred to as the "solar wind." Because of this flow, the magnetosphere may be deformed into the shape of a tear drop with a tail pointing away from the Sun (Ref. 3). The magnetosphere is bounded on its interior by the ionosphere (altitude, 100 to 300 km) and the insulating, air layer lying below it. There are large-scale current systems in the ionosphere which cause regular, daily variations in the magnitude and direction of the geomagnetic field (Ref. 4). Large perturbations of the geomagnetic field are associated with ionospheric currents located near the auroral zones.

The question of whether a ring current exists or not is very important because it is related to many fundamental problems concerning the Earth's outer atmosphere and its interaction with the interplanetary medium. (1) The ring current may play a crucial role in magnetic storms. The growth and subsidence of the ring current could be responsible for certain characteristic features of the storms that are observed at the Earth's surface. (2) The ring current may be intimately related to the aurorae. The charged particles in the ring current may either cause the aurorae or so perturb the distant geomagnetic field that particles can reach the polar atmosphere which might not do so otherwise. (3) The properties and dynamics of the Earth's outer atmosphere could be strongly influenced by the presence of a ring current. If magnetic storm and auroral effects are indeed caused by a ring current, then the charged particles which cause the current are an important constituent of the outer atmosphere. The origin and characteristics of these particles would represent important information. The existence of the ring current and its dynamic, or time-dependent, variations may imply that trapping and loss mechanisms are operating in the magnetosphere, or that modes of energy exchange exist for a collisionless plasma.

The following discussion of the ring current will consist of two major parts. Section II is a theoretical discussion of how a ring current can originate and be maintained. In Section III, the experimental evidence concerning the existence of the ring current will be presented and discussed. Measurements made on Earth satellites and space probes will be emphasized.

II. THEORY

The following discussion will trace the historical development of ring current theory. This approach is employed because the fairly sophisticated, modern theory can be most readily understood by seeing how it evolved from simpler, and more naive, concepts. Furthermore, this approach gives dramatic emphasis to an important difference between the modern theory and the earlier explanations. The older theories, though based on simple concepts and simple mathematical models, involved ad hoc assumptions and unnatural, or artificial, physical situations. On the other hand, in the modern theory, the ring current arises in a natural way, with a minimum number of assumptions, even though the physical concepts and mathematics are more complicated. This combination of history and theory is intended to be an accurate record, except that I have taken the liberty of going beyond some of the original works in an attempt to recreate the motivation for each.

Historically, the primary goal of ring current theory has been to solve the steady-state problem. The basic question has been: How can such a current system be maintained? This preoccupation with the steady state will be adhered to in the following discussion except for a few comments on the origin and decay of the ring current.

A. Stoermer's Theory

In 1911, the famous mathematical physicist, Carl Stoermer, postulated that a ring current encircled the Earth at very great altitudes (Ref. 5). This postulate was part of Stoermer's attempt to explain the aurorae. He was an advocate of an explanation proposed by Birkeland shortly before the turn of the century which is still given serious consideration. The basic concept is that the auroral emissions (electromagnetic radiation from gases in the upper atmosphere) are excited by the bombardment of particles from interplanetary space. According to this explanation, charged particles emitted by the Sun, which arrive in the vicinity of the Earth, are deflected toward the poles by the geomagnetic field. Stoermer undertook a theoretical study of the motion of a charged particle in a magnetic-dipole field.

One of the most important results of his analysis was that, for particles entering the Earth's field from outside, there are regions of space into which the particles cannot enter, the so-called "forbidden zones." In order for particles to penetrate close to the Earth's surface, a certain, minimum kinetic energy is required. It was known that approximately one and a half days elapsed between a solar flare and the associated magnetic storm and aurorae. Thus, the time required for the particles to propagate from the Sun to the Earth implies an average velocity of 1000 km sec^{-1}. Since the Sun is composed primarily of hydrogen, it is likely that such particles would be protons. These two pieces of information provide an estimate of the kinetic energy of the incoming particles ($\sim$20 kev). It was clear from Stoermer's analysis that such low energy particles could only reach the Earth in the immediate vicinity of the magnetic poles. However, the auroral zones, i.e., the range of latitudes inside which auroral activity is most common, are located at a geomagnetic latitude of approximately 68°, or 22° from the poles. This paradox represented a fundamental obstacle to the acceptance of the auroral theory.

In an attempt to resolve this dilemma, Stoermer invoked a westward ring current. Such a current would produce a large scale magnetic field directed southward interior to itself. (This can be seen most simply by employing the right hand rule.) Since the geomagnetic field is directed northward (the north magnetic pole is located near the south geographic pole), the ring current field would oppose, or "weaken," the geomagnetic field. The reduced strength of the field surrounding the Earth could permit low energy particles to reach the Earth at lower latitudes, i.e., in the vicinity of the auroral zones.

In addition to postulating the existence of the ring current, Stoermer attempted to explain how such a current could arise, i.e., what sort of orbits the charge particles would move in which produced the current. The force exerted on a charged particle moving in a magnetic field is given by the Lorentz force law (in MKS units)

$$\mathbf{F} = e\mathbf{v} \times \mathbf{B} \qquad (1)$$

where e is the charge on the particle, v is the particle velocity, and B is the magnetic field. Since the force is transverse to both v and B, no work is done on the particle by the field (its kinetic energy is constant) and the effect of the field is merely to cause the particle to circle about the field lines. In the simple orbit proposed by Stoermer, the particles moved in equatorial circular orbits about the Earth (Fig. 1). The centrifugal reaction,

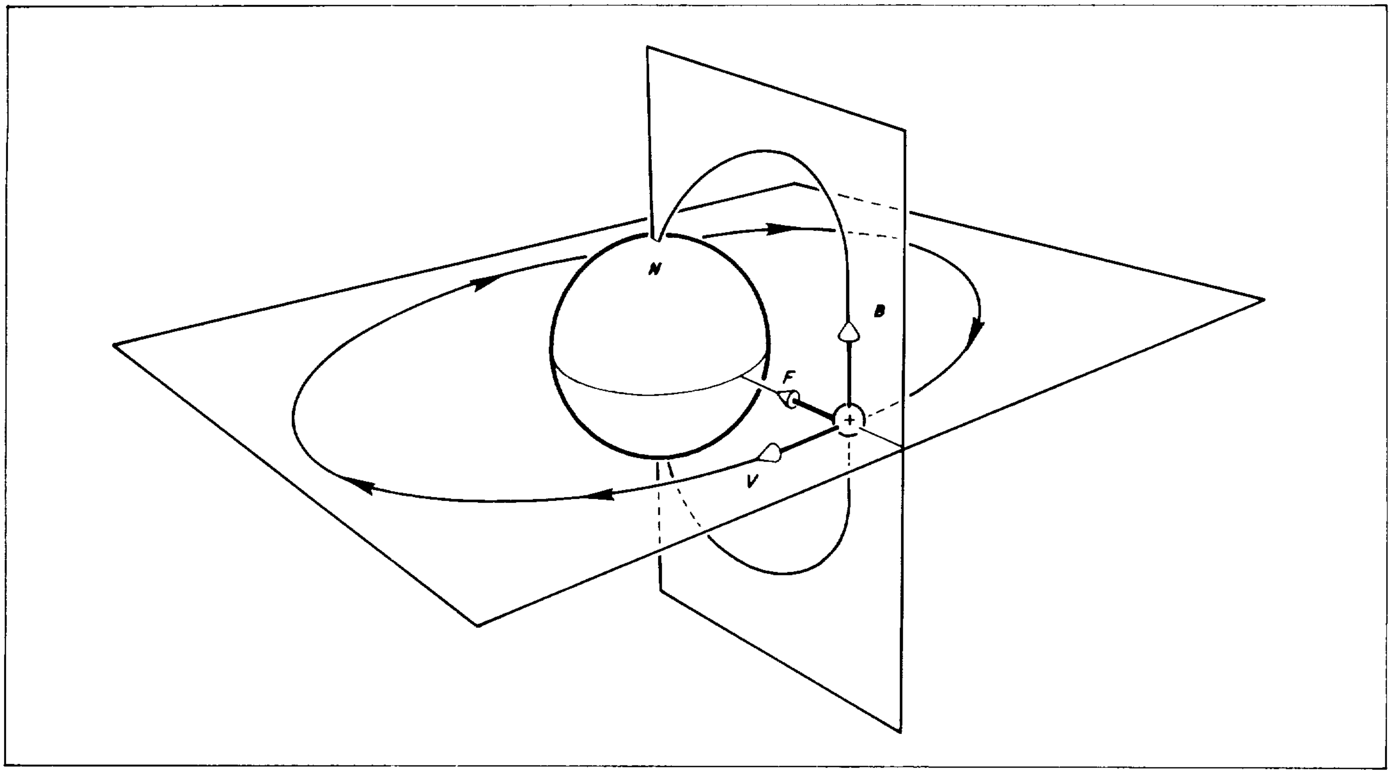

Fig. 1. Stoermer ring current

(mv^2/R) (m is the particle mass and R is the location of the orbit from the center of the Earth), was exactly compensated by the centripetal Lorentz force. Thus,

$$\frac{mv^2}{R} = evB \qquad (2)$$

The magnitude of the geomagnetic field in the equatorial plane is given by

$$B = \frac{\mu_0}{4\pi}\frac{M}{R^3} \qquad (3)$$

where M is the Earth's magnetic dipole moment. Combining these equations, the radius can be found at which this condition is fulfilled, namely

$$R = \left[\frac{\mu_0 Me}{4\pi mv}\right]^{1/2} \qquad (4)$$

(This distance is frequently written c_{st} and called the Stoermer unit.)

If representative values of m and v are substituted in Eq. (4), e.g., protons with a velocity of 1000 km sec^{-1}, then $R = 150\ R_E$. Since the distance from the Earth to the Moon is approximately 60 R_E, the ring current proposed by Stoermer would be located far outside the orbit of the moon!

Stoermer's ring current theory is primarily of historical interest. Criticisms were very quickly raised which the theory could not overcome. The fundamental problem of both the ring current theory, and this particular version of auroral theory, was that only particles of one sign were involved. In the case of the ring current, for example, the mutual electrostatic repulsion between the positively charged particles would quickly dispel the current, provided the particles were able to get into these rather peculiar and special orbits in the first place. The large-scale neutrality of ionized gases, such as those emitted by the Sun, is now a well-established principle of cosmic electrodynamics.

Stoermer was unable to develop a satisfactory theory of the ring current. Furthermore, it may be that his auroral theory is incorrect; it appears now that the particles that cause the aurorae may be stored in the magnetosphere before being "dumped" into the high latitude, auroral zone. However, Stoermer's suggestions and analysis are still of great value. His analysis of the motion of individual particles in the geomagnetic field has been applied successfully to cosmic rays and to high-energy solar protons. His analysis of the effect a ring current would have on the trajectories of particles is still valid. It is a fact that the auroral zones move toward lower latitudes during the main phase of magnetic storms (Ref. 6). The creation or intensification of a ring current could be responsible. Furthermore, variations in the intensity of solar protons arriving at a normally forbidden latitude as a function of magnetic storm phase are also consistent with the effects caused by a ring current (Ref. 7).

Historically, the effect of the ring current on the aurorae has been of secondary interest. The primary motive in ring current theory has been to explain certain aspects of magnetic storms. Subsequent theories of the ring current are closely related to magnetic storm effects, although it has been common to try to explain both magnetic storms and aurorae with a single theory.

B. The Chapman-Ferraro Theory

The steady geomagnetic field is subject to "storms" at an average rate of three or four days per month. The characteristic feature of magnetic storms is the occurrence of fluctuations in the field elements (horizontal intensity, declination, dip, etc. (Ref. 4 and 8). The typical period of these fluctuations can range from an hour to less than a second. The corresponding magnitude changes may vary between several hundred or a thousand gamma to a fraction of one gamma. (1 gamma = 10^{-5} gauss, approximately one fifty-thousandth of the Earth's field at the surface.) This *irregular* component of the storm field is strongly latitude dependent and the maximum amplitude occurs in the auroral zone.

In addition to these rapid changes in the storm field, there is a *regular*, long period component (hours to days) which exhibits a characteristic behavior during magnetic storms. Changes in the horizontal field intensity provide the simplest and most direct evidence of this tendency of the gross features of magnetic storms to be reproducible. The typical time dependent behavior of the horizontal component (Fig. 2) is as follows:

1. The beginning of the storm (the *initial phase*) is accompanied by an increase in average field intensity. A typical value for the peak of the initial phase is $\sim 20\ \gamma$. This phase usually lasts several hours, after which the average horizontal intensity has returned to its prestorm value.
2. The average intensity continues to decrease to a value less than the prestorm value (the *main phase*). It reaches a minimum value in, perhaps, one day. A typical value of the average field change during the main phase is $100\ \gamma$.
3. There is a gradual recovery to the quiescent, prestorm value requiring one to two days (the *recovery phase*).

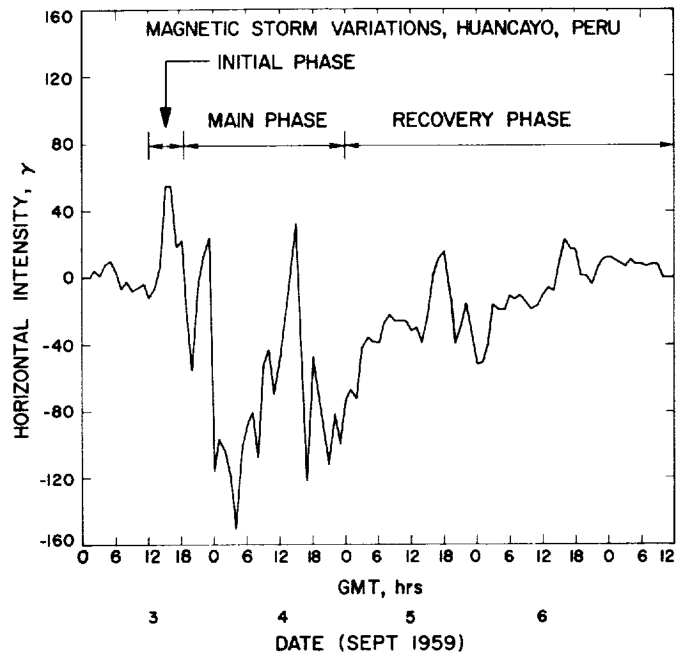

Fig. 2. Variation in the horizontal intensity of the Earth's field during a magnetic storm

In 1916, Adolph Schmidt attempted to explain the "main phase decrease." From a study of magnetograms made at the Earth's surface, he postulated the existence of the ring current (Ref. 9). He also suggested that the current died away so slowly that it was a common feature of the region of space surrounding the Earth.

Beginning in 1931, Chapman and Ferraro developed a comprehensive theory of magnetic storms (Ref. 10). Their theory involved many concepts which are still widely accepted, although somewhat modified. The starting point of the Chapman-Ferraro storm theory is the emission by the Sun of a neutral, ionized gas cloud. This plasma cloud travels toward the Earth, and the magnetic storm is initiated by a collision between the ionized gas and the distant geomagnetic field. The plasma cloud is diamagnetic, i.e., it tends to exclude magnetic fields from its interior. As a result, it compresses the geomagnetic field into a hollow inside the cloud. This feature, which was used by Chapman and Ferraro to explain the initial phase of magnetic storms, has since been extended to non-storm conditions. The cavity discussed in the introduction is frequently referred to as the Chapman-Ferraro cavity.

Chapman and Ferraro were able to relate the magnitude of the initial phase of the storm to the distance from the center of the Earth to the ionized cloud. For a typical value of 20 γ, the corresponding distance was approximately 10 R_E.

In order to explain the main phase decrease, Chapman and Ferraro also invoked a ring current. Obviously, such a current should lie inside the cavity containing the geomagnetic field. To be consistent with the predictions of the theory regarding the initial phase, this implied that the ring current was located within 10 R_E of the Earth's center.

The basic problem confronting Chapman and Ferraro was to establish such a current system at an altitude of 10 R_E or less. As we have seen, Stoermer's theory had particles moving in circular orbits, but the orbits were located at very great distances (150 R_E). The fundamental difficulty can be stated another way. The centrifugal reaction of a particle moving in a circular orbit of radius 10 R_E is approximately 10^{-18} dynes (for 20 kev protons as above). On the other hand, the magnitude of the geomagnetic field at 10 R_E is 100 γ and the corresponding Lorentz force, evB, is 10^{-15} dynes. Clearly, another force was required in order to compensate for the very large Lorentz force. Chapman and Ferraro suggested that the compensating force was provided by an electric field. The electric field was caused by the separation of positive and negative charges.

The Chapman-Ferraro ring current is shown in Fig. 3. The positive charges (protons) move toward the west with velocity, v_p, provided the Lorentz force exceeds the outward electrostatic force. Hence,

$$\frac{m_p v_p^2}{R} = Bev_p - eE \qquad (5)$$

The negative charges (electrons), on the other hand, have a *centripetal* force exerted on them by the electric field. Hence, the Lorentz force must be oppositely directed, or outward. This implies that the electrons also move toward the west (with velocity, v_e), so that

$$\frac{m_e v_e^2}{R} = eE - eBv_e \qquad (6)$$

The westward moving electrons represent an eastward current which tends to compensate the westward current associated with the protons. However, adding the two equations above,

$$\frac{m_p v_p^2}{R} + \frac{m_e v_e^2}{R} = eB\,(v_p - v_e) \qquad (7)$$

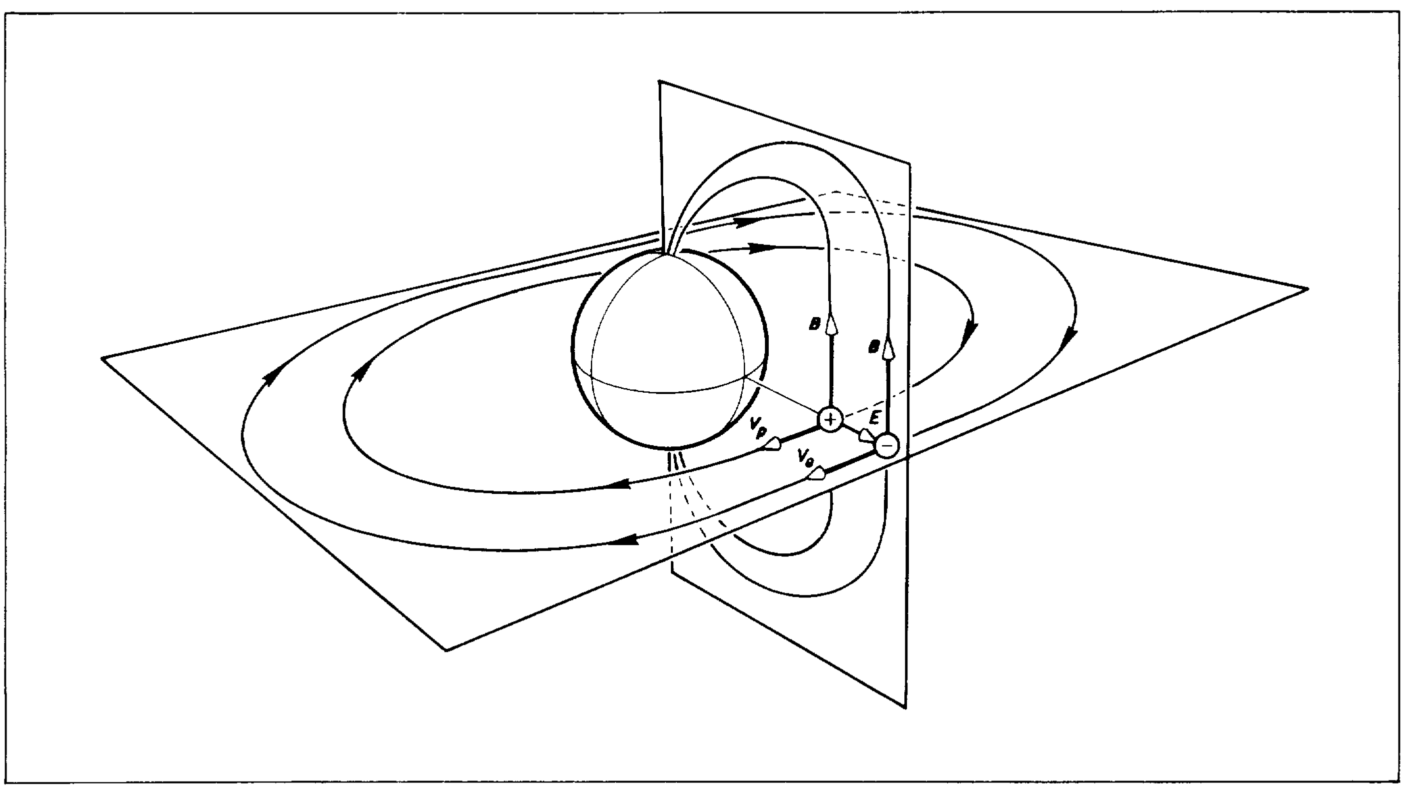

Fig. 3. Chapman-Ferraro ring current

Since the left-hand side of the equation is positive, $v_p > v_e$, and the net current flow is westward. This is required by the observed direction of the large-scale main phase storm field.

This rather ingenious mechanism for maintaining the ring current was subject to several serious criticisms. Although Chapman and Ferraro suggested that such a current might be established by a discharge across the cavity by particles of opposite sign, there was really no mechanism to establish such a curious physical situation. Furthermore, Alfvén questioned the stability of such a current, assuming it were possible to place the particles in these unique orbits (Ref. 11). He attempted to show that any perturbation would quickly lead to a disruption of the current flow. The Chapman-Ferraro theory of the ring current was given serious consideration as late as 1957; however, it has since been abandoned in favor of the modern theory of the ring current to be discussed below. Chapman has accepted the modern explanation and is presently involved in detailed calculations of the associated magnetic field.

C. *Alfvén's Electric Field Theory*

Beginning in 1939, H. O. Alfvén attempted to show that both magnetic storms and aurorae are caused by the interaction between the geomagnetic field and incident solar plasma (Ref. 12). Alfvén studied the trajectories of the plasma particles in interplanetary space and in the geomagnetic field. His theory indicated that, as the solar cloud passes near the Earth, the particle motions include a component which, in effect, represents a ring current. This ring current gives rise to the main phase decrease, as in the Chapman-Ferraro theory, however, the origin of the current is quite different in the two theories. In Alfvén's theory, the ring current particles are not trapped inside the geomagnetic field.

Alfvén's theory is more sophisticated than either of the theories discussed above. It involves many subtleties that have been incorporated into the modern ring current theory. Therefore, it will be helpful to review the general aspects of the storm theory before becoming involved in the physical and mathematical details.

The starting point of Alfvén's theory is the physical state of the solar plasma as it travels through interplanetary space toward the Earth. Alfvén postulated that a regular, interplanetary magnetic field exists (presumably a solar field). As the conducting plasma moves through the interplanetary field, it contains a large scale electric field. The charged particles in the plasma cloud move in spirals about the interplanetary magnetic field and represent tiny, magnetic dipoles. As the gyrating particles near the Earth, a repulsive force is exerted on them by the inhomogeneous, geomagnetic, dipole field. The Earth's field gradient deflects the positive and negative charges toward opposite sides of the Earth.

The field gradient also causes an ion-electron velocity difference. This causes westward currents on both sides of the Earth which are *equivalent* to a ring current. Due to the lateral displacement of the particles, they extract energy from the large-scale electric field surrounding the Earth. The increased kinetic energy allows them to enter the geomagnetic field, although there exist certain forbidden regions concentric with the Earth into which the particles cannot penetrate. The magnetic storm field at the Earth's surface is due not only to the ring current, but there is also a field component associated with the spiral motion of the particles, which represent an aggregate of tiny magnetic dipoles. The particles pass around the Earth and continue on into interplanetary space. The magnetic storm terminates when all the plasma passes beyond the Earth's orbit.

The mathematical details of Alfvén's theory involve: (1) the character of the electric field inside the plasma, (2) the velocities of the particles as they pass the Earth, and (3) the equation of motion, or the trajectories, of the particles. Following Alfvén, we shall assume, for simplicity, that all particle motion is confined to the Earth's equatorial plane.

1. The Electric Field

It is well known that, if a solid conductor is transported through a magnetic field, the conductor becomes electrically polarized (Ref. 13). Positive and negative charges appear on opposite faces of the conductor, transverse to the magnetic field. The polarization is caused by the Lorentz force which deflects charges of opposite sign in opposite directions. Charge separation continues until an electric field is produced which compensates the Lorentz force per unit charge.

In the case of a *plasma* moving through a magnetic field, the basic motion of the particles is a spiraling about the magnetic field caused by the Lorentz force. Consider the equation of motion of a particle in combined electric and magnetic fields:

$$m\dot{\mathbf{v}} = e\mathbf{E} + e\mathbf{v} \times \mathbf{B} \qquad (8)$$

In many physical situations the motion of the particle can be separated into two components: (1) motion about an instantaneous center of rotation, called the *guiding center,* and (2) a translation. For example, let

$$\mathbf{v} = \mathbf{v}_G + \mathbf{v}_D \tag{9}$$

$$m\dot{\mathbf{v}}_G = e\mathbf{v}_G \times \mathbf{B} + e\left[\mathbf{E} + \mathbf{v}_D \times \mathbf{B} - \frac{m}{e}\dot{\mathbf{v}}_D\right] \tag{10}$$

There is a steady state solution ($d\mathbf{v}_D/dt = \dot{\mathbf{v}}_D = 0$) in which the term inside the bracket vanishes so that

$$m\dot{\mathbf{v}}_G = e\mathbf{v}_G \times \mathbf{B} \tag{11}$$

$$\mathbf{v}_D \times \boldsymbol{B} = -\mathbf{E} \tag{12}$$

The former is the equation of motion of a particle in a magnetic field. Taking the cross product of B with the latter equation, one obtains:

$$\mathbf{v}_D = \frac{\mathbf{E} \times \mathbf{B}}{B^2} \tag{13}$$

Thus, under the action of crossed electric and magnetic fields, particles drift in a direction transverse to both (Fig. 4). Alternatively, plasma transported through a field with velocity, v_D, will give rise to an electric field, $\mathbf{E} = -\mathbf{v}_D \times \mathbf{B}$. Note that the direction and magnitude of the drift velocity is the same for both positive and negative particles so that, in a neutral plasma, there is no net current.

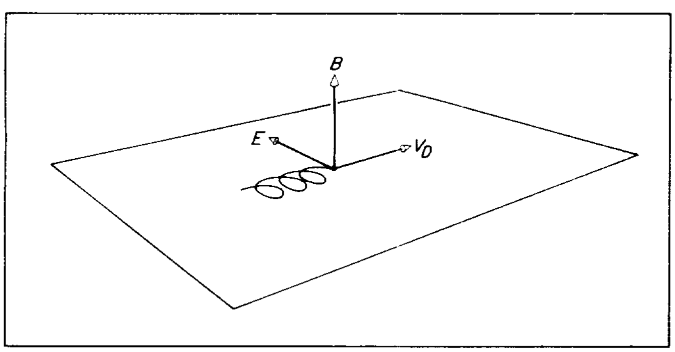

Fig. 4. Motion of a charged particle in crossed electric and magnetic fields

The separation of the particle motion into a spiral motion superposed on a steady drift is an important feature of modern ring current and plasma theory. The drift velocity, v_D, is typically much smaller than the velocity associated with the gyration, v_G (corresponding to the kinetic energy). This condition is essential, since the so-called *guiding center approximation* is only valid provided there is only a small change in B due to the drift during one gyro period.

2. Particle Velocity Inside the Geomagnetic Field

The spiral motion of the particle gives rise to a magnetic dipole moment μ. The circular motion of the particle is equivalent to a current, $i = e/T$, T being the gyro period. The magnetic moment of the equivalent current loop is iA, where A is the area enclosed. Since

$$A = \pi\rho^2 \qquad \rho = \frac{mv\perp}{eB}$$

and

$$\frac{2\pi}{T} = \frac{e}{m}B$$

then

$$\mu = \frac{\frac{1}{2}mv\perp^2}{B} = \frac{w\perp}{B} \tag{14}$$

The Lorentz force is transverse to $v\perp$ and cannot increase the transverse kinetic energy of the particle, hence, μ is a constant. The direction of the magnetic moment is the same for both ions and electrons, i.e., antiparallel to the magnetic field.

A plasma in a magnetic field represents an aggregate of magnetic dipoles rather than a simple collection of charged particles. Hence, the bulk motion of the plasma depends on the forces which can be exerted on the magnetic dipoles. When such a force occurs, the dipoles begin to drift. This gives rise to a secondary Lorentz force, $e\mathbf{v}_D \times \mathbf{B}$, since the motion of the dipole involves the transport of charge through a magnetic field. In equilibrium, the secondary Lorentz force must just compensate the force acting on the elementary dipole. Thus,

$$e\mathbf{v}_D \times \mathbf{B} + \mathbf{F} = 0 \tag{15}$$

Since

$$e\mathbf{v}_D \times \mathbf{B} \times \mathbf{B} = -eB^2\,\mathbf{V}_D, \tag{16}$$

$$\mathbf{v}_D = \frac{\mathbf{F} \times \mathbf{B}}{eB^2} \tag{17}$$

(If F is caused by an electric field we recover Eq. 13 above)

As long as F is independent of the sign of the charge, a current will result. Thus, currents inside neutral plasmas are caused by forces and not by electric fields. This result is contrary to our normal, every-day experience with conductors, where an electric field is almost always the cause of a current.

The Alfvén storm theory is based on the force exerted on the magnetic dipoles by the inhomogeneous geomagnetic field. A magnetic dipole placed in a field gradient will experience a force,

$$\mathbf{F} = \nabla (\boldsymbol{\mu} \cdot \mathbf{B}) \tag{18}$$

thus,

$$\mathbf{v}_D = \frac{1}{eB^2} \nabla (\boldsymbol{\mu} \cdot \mathbf{B}) \times \mathbf{B} = -\frac{\mu}{eB^2} \nabla B \times \mathbf{B} \tag{19}$$

Since the gradient of the geomagnetic field is directed toward the Earth, and **B** is northward on the geomagnetic equator, ions will drift toward the west and electrons toward the east (Fig. 5). The resulting current density is given by

$$\mathbf{J} = e(n^+ \mathbf{v}_D^+ - n^- \mathbf{v}_D^-) \tag{20}$$

Since

$$\mathbf{v}_D^+ = \frac{\mathbf{E} \times \mathbf{B}}{B^2} - \frac{w_\perp^+}{eB^2} \nabla B \tag{21}$$

and

$$\mathbf{v}_D^- = \frac{\mathbf{E} \times \mathbf{B}}{B^2} + \frac{w_\perp^-}{eB^2} \nabla B, \tag{22}$$

$$\mathbf{J} = -n (w_\perp^+ + w_\perp^-) \frac{\nabla B}{B^2} \tag{23}$$

The negative sign implies that the current due to both ions and electrons is westward. The deflection of the electrons toward the east produces a westward current because of their negative charge.

The major contribution to the storm field comes from this westward current. Alfvén also called attention to another component of the storm field. The resultant field, obtained by summing fields from each of the elementary dipoles, increases the magnitude of the geomagnetic field at the Earth's surface and diminishes it inside the plasma. This fundamental property of plasmas is called *diamagnetism* (see Sec. 2-D-(3) below). Alfvén showed that, at the Earth's surface, the diamagnetic component is only one third of the field magnitude associated with the drift current. Therefore the dominant westward current causes a decreased field at the surface (the main phase).

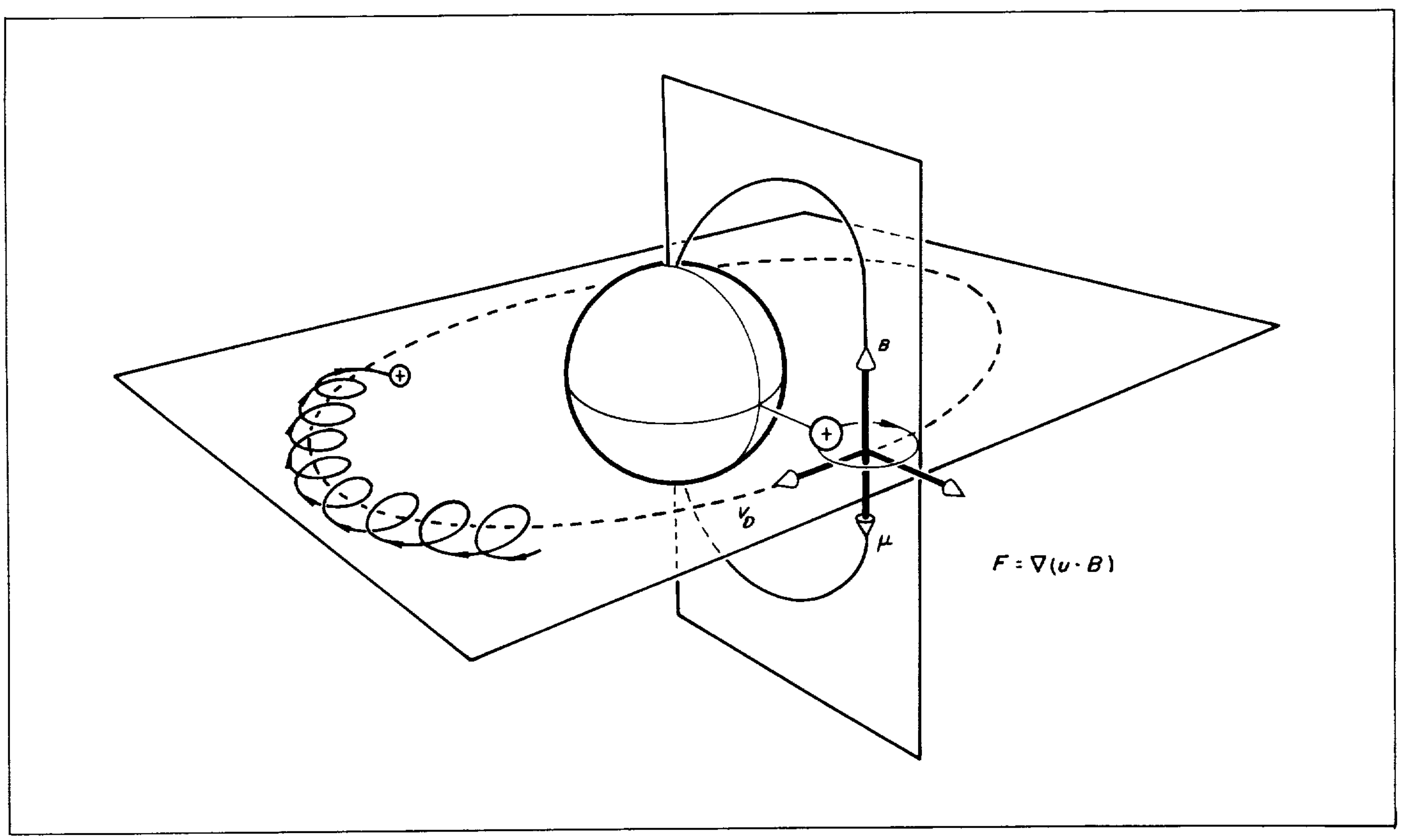

Fig. 5. Alfvén drift velocity for a particle in the inhomogeneous geomagnetic field

3. Equation of Motion of the Plasma

The discussions above have provided a description of the physical state of the solar plasma in interplanetary space and the currents inside a plasma in the geomagnetic field. Alfvén's theory also relates the characteristics of the particles in the two regions of space. Alfvén shows how the particles are able to enter the geomagnetic field and he derives the equation of motion of the guiding centers. For simplicity, he assumes that the motion of the particles is confined to the equatorial plane.

In the guiding center approximation, all field changes are slow compared to the gyro period of the particles and the magnetic moment of the particles is a constant of motion. The magnetic movement in the approaching plasma cloud is given by

$$\mu = \frac{w_0}{B_0} \qquad (24)$$

where w_0 is the transverse kinetic energy of the particle, and B_0 is the magnitude of the interplanetary magnetic field.

If a particle enters the geomagnetic field, B_0 is augmented by G, the magnitude of the geomagnetic field. Since μ must remain constant, the kinetic energy of the particles must increase in order for them to penetrate into the geomagnetic field. But the particles are in a large-scale electric field, so they can gain kinetic energy by developing a lateral component of motion. A component of motion parallel to E will result in a decreased electric potential and an increased kinetic energy. As we have seen, due to the inhomogeneity of the Earth's field, forces are actually exerted on the particles which cause them to drift laterally. Hence,

$$\mu = \frac{w_0}{B_0} = \frac{\frac{1}{2}mv^2 + eE\triangle X}{B_0 + G(x,y)} \qquad (25)$$

X and Y are the coordinates of a guiding center in the equatorial plane, and $\triangle X$ is the lateral displacement of the guiding center in the electric field.

This is essentially an expression for X as a function of Y, i.e., the equation of motion of the particles. Alfvén used Eq. (25) to compute the trajectories of the guiding centers. The motion of the electron guiding centers are shown in Fig. 6. The motion of the ions are essentially the mirror images of the electron trajectories.

Mathematically, solutions of the above equation only exist outside certain zones which are inaccessible to the

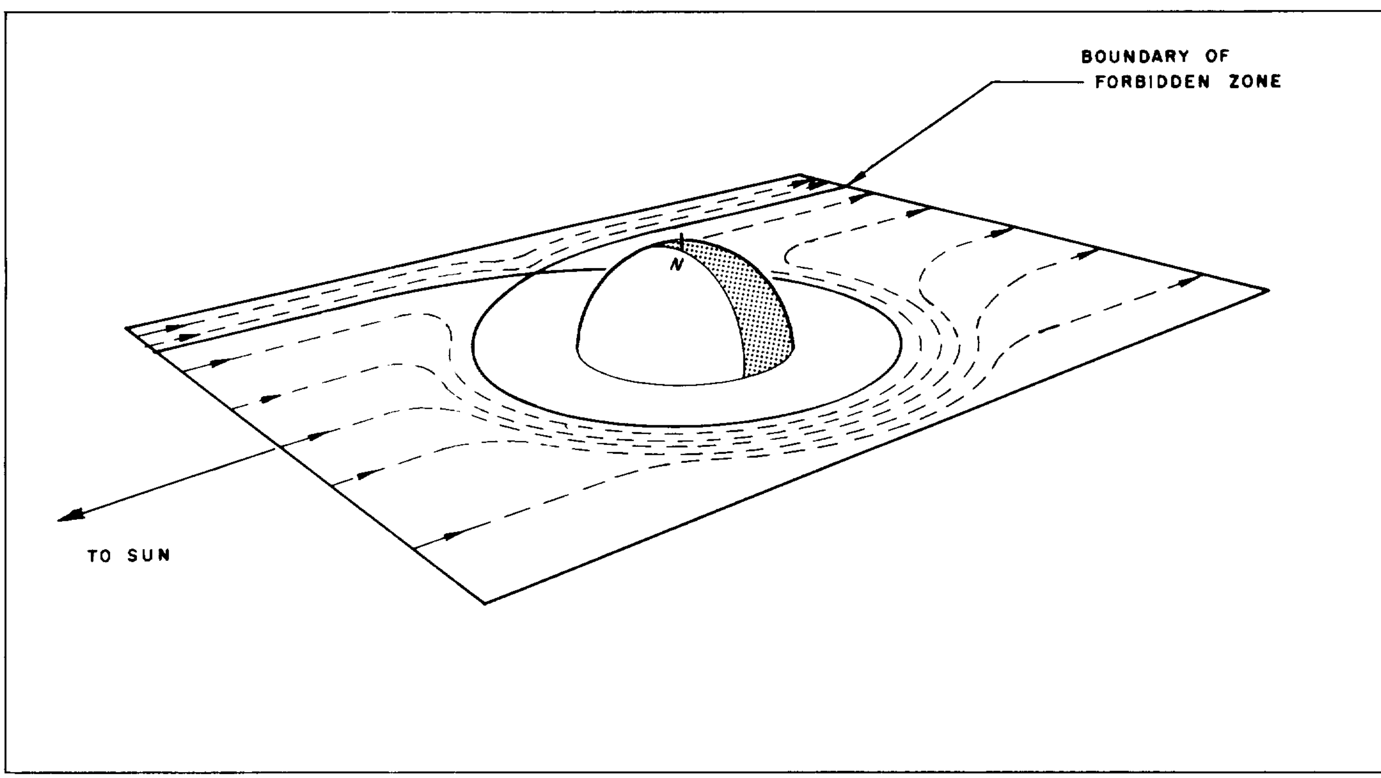

Fig. 6. Motion of the electron guiding centers according to Alfvén's theory

particles. The physical basis for the existence of forbidden regions is that there is a maximum amount of energy which a particle can extract from the electric field. There are forbidden zones for both electrons and ions. In general, the boundaries of the forbidden zones will not coincide.

The validity of Alfvén's storm theory is still a controversial subject. Alfvén has persisted in his views. New information, which has been forthcoming since Alfvén proposed his theory, has produced concepts of magnetic storm phenomena, that are different from those adopted by Alfvén. The differences apply to almost all aspects of Alfvén's theory: the initial conditions in interplanetary space prior to the solar disturbance which causes the storm, the physical state of the solar plasma as it approaches the Earth, and the interaction between the plasma and the geomagnetic field.

In all three theories discussed above, it was assumed that interplanetary space, and the space surrounding the Earth, was a vacuum. The solar plasma was assumed to propagate into regions containing vacuum magnetic fields. However, there is now experimental evidence that both interplanetary space and the Earth's magnetosphere contain plasma (Ref. 14, 15, and 16). The plasma number density in both regions is estimated at 1-100 particles cm^{-3}, a density which may be greater than the density of the plasma associated with a solar disturbance. Furthermore, the ambient, interplanetary plasma is streaming outward from the Sun (Ref. 17). An interplanetary magnetic field exists, but its configuration is quite different than it would be in a vacuum. For example, solar magnetic field lines are spiraled, non-uniform and irregular (Ref. 18). Neither of these conditions were anticipated by Alfvén's theory.

It is now commonly thought that the plasma emitted by the Sun causes a hydromagnetic shock wave as it propagates toward the earth (Ref. 19, 20, and 21). The physics of such a collisionless shock will certainly be different than it would be for an aggregate of individual particles in a strong magnetic field.

The modern views of the interaction between the solar plasma and the geomagnetic field are strongly conditioned by the expectation that there is an interface between the Earth's magnetosphere and interplanetary space. If the latter were actually a vacuum, an interplanetary field might simply merge with the geomagnetic field, as assumed by Alfvén. However, the present theoretical view is that a complex hydromagnetic boundary-value problem is involved in which the ionized, interplanetary gas confines the geomagnetic field, and the associated terrestrial plasma, to a rather well-defined volume of space. Thus, injection mechanisms are required in order to transfer particles from interplanetary space into the magnetosphere. Alfvén is virtually alone in arguing that the plasma can enter the magnetosphere directly.

From the standpoint of ring current theory, the most important feature of Alfvén's storm theory was his use of the guiding center approximation. Stoermer, and Chapman and Ferraro, proposed ring current models in which charged particles move in large, circular orbits concentric with the Earth. Alfvén showed that particles can spiral about magnetic lines of force in small circular orbits which are not concentric with the Earth, but which give rise to a current because of a slow drift of the guiding center. This concept overcomes the handicaps of the earlier theories because the Lorentz force which causes the particles to spiral, can be orders of magnitude larger than the forces which cause the guiding center to drift. This fundamental result is the basis of the modern ring current theory. Alfvén also recognized that there were diamagnetic effects associated with the plasma and these are also an important feature of modern ring current theory.

D. *Modern Ring Current Theory*

In 1957, S. F. Singer set forth a hypothesis which provided the basis for what we may call the Modern Ring Current Theory (Ref. 20). His hypothesis was directly related to Stoermer's analysis of the trajectories of particles which enter the geomagnetic field. Stoermer established that there were forbidden zones into which an incident particle could not penetrate. Similarly, particles inside the forbidden zone are trapped by the geomagnetic field and move in captive orbits from which they cannot escape.

The trajectory of a trapped particle consists of a helical path which tends to follow geomagnetic field lines but has an azimuthal component. The representation of the complex particle motion was simplified by Alfvén, who used a perturbation technique, namely, the guiding center approximation discussed above (Ref. 12). Alfvén showed that the guiding center of the trapped particle travels up and down in the magnetic field while drifting around the Earth, much like one of the horses on a carousel.

Singer suggested that during a magnetic storm, solar particles were trapped in Stoermer's forbidden regions. This was a direct violation of Stoermer's results for incident particles. Singer showed, however, that the motion of the trapped particles is equivalent to a westward current, which he identified with the main phase ring current. The strength of Singer's hypothesis is that it is only necessary to make a single assumption in order to establish a ring current, i.e., that there are particles in trapped orbits.

This assumption is reasonable if one allows any one of a fairly large number of trapping mechanisms to operate so that Stoermer's analysis is invalidated. Singer, for example, suggested that a bubble of gas containing many particles can deform the geomagnetic field locally so that it was no longer dipolar. It has also been suggested that small irregularities in the solar plasma can diffuse into the Earth's field, or that solar particles can be scattered into the trapped orbits by hydromagnetic shock waves (Ref. 22 and 23).

Irrespective of a detailed understanding of injection mechanisms, we know that particles are actually trapped in these captive orbits. The high energy particles of the Van Allen radiation zones move along the trajectories studied by Stoermer, Alfvén, and Singer. There appears to be an adequate injection mechanism to explain the high energy protons found in the inner zone, namely, the decay of neutrons caused by cosmic rays (Ref. 24, 25, and 26). However, at the present time, the origin of the outer zone is unknown.

When the radiation zones were first discovered, it was thought that the radiation particles might be responsible for the ring current. However, subsequent investigations have shown that the radiation particles do not cause a current system of sufficient magnitude to account for the geophysical effects (such as the main phase decrease) usually attributed to a ring current. It is likely that there is a current system associated with the radiation particles, however, it is apparently a very weak current.

The ring current may be caused by trapped particles other than the radiation particles. If the average kinetic energy of such particles is much less than the average kinetic energy of the radiation particles, their presence would not be detected by the radiation particle detectors. Such detectors only respond to the high-energy particles. Although the average kinetic energy per ring current particle may be much less than the average kinetic energy per Van Allen particle, there are, presumably, many more of them. Thus, the kinetic energy density, total kinetic energy, and the current associated with the ring current particles could be large. *The ring current particles may have orbits which are essentially the same as the orbits of the radiation particles.* The trapped particles spiral about the magnetic lines of force while traveling back and forth between "mirror points" in the northern and southern hemispheres.

How do trapped particles cause a ring current? As in Alfvén's theory each spiraling particle has a magnetic moment. The repulsive force exerted on this moment by the geomagnetic field gradient causes the guiding center to drift and a westward current is the result.

The guiding center will also drift because of the curvature of the geomagnetic lines of force. Singer used some numerical results worked out by Alfvén to describe the motion of particles in the Stoermer orbits. Singer's results implicitly contained this component of the drift, which was not included in Alfvén's storm theory. Subsequently Dessler and Parker derived an explicit expression for the current density associated with the curvature drift (Ref. 22).

Dessler and Parker also called attention to a third current component associated with the diamagnetism of the plasma. Diamagnetism causes virtual, or fictitious, currents to flow. Diamagnetic currents are not drift currents associated with forces exerted on individual particles, but arise in an aggregate of spiraling particles.

To summarize the present theoretical view, a diamagnetic ring current is caused by trapped plasma. The ring current is actually the sum of three ring currents associated with (1) gradient drift, (2) curvature drift, and (3) diamagnetism.

1. Gradient Drift

The basic physics of the two drift currents is the same as in the Alfvén storm theory (Fig. 7). Under the action of a force, the guiding center drifts with a velocity given by Equation (17).

$$\mathbf{v}_D = \frac{\mathbf{F} \times \mathbf{B}}{eB^2} \tag{17}$$

When F is the force exerted by the Earth's field gradient, the drift velocity is

$$\mathbf{v}_\mu = -\frac{w\perp}{eB^2} \nabla B \times \mathbf{B} \tag{26}$$

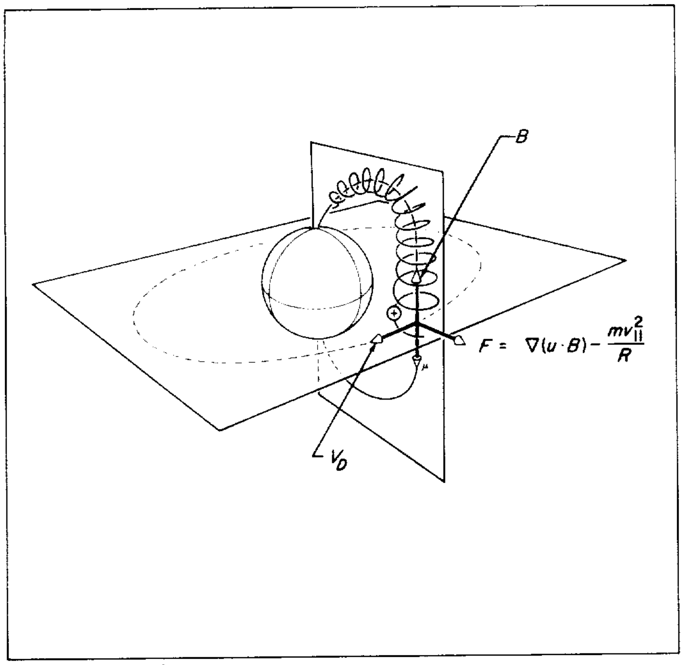

Fig. 7. Drift velocity of a particle trapped in the geomagnetic field

The corresponding current density is

$$\mathbf{J}\mu = ne\mathbf{v}\mu = -\frac{w\perp}{B^3}\nabla B \times \mathbf{B} \qquad (27)$$

n is the particle number density, and $W\perp = \frac{1}{2}nmv\perp^2$ is the total transverse kinetic energy density. The current is westward for both protons and electrons. On the equator, the magnitude of the current density is

$$\mathbf{J}\mu = \frac{W\perp}{B^2}\nabla B \qquad (28)$$

2. Curvature Drift

A centripetal force is required to keep a trapped particle moving along the curved geomagnetic field lines. The centripetal force is provided by a secondary Lorentz force, $e\mathbf{V}_R \times \mathbf{B}$, which just compensates for the centrifugal reaction of the particle. The latter is equivalent to a force:

$$F = -\frac{mv_{||}^2}{R}\hat{e}_R \qquad (29)$$

V_R is the drift velocity due to the curvature. R is the radius of curvature of the field line having a direction, $\hat{e}_R$ (a unit vector). Substituting in the fundamental equation (Eq. 17),

$$\mathbf{V}_R = -\frac{mv_{||}^2}{eB^2R}\hat{e}_R \times \mathbf{B} \qquad (30)$$

If there are n particles per unit volume with a total, longitudinal kinetic energy density, $W_{||}$,

$$J_R = -\frac{2W_{||}}{B^2R}\hat{e}_R \times \mathbf{B} \qquad (31)$$

On the equator, the magnitude of the curvature drift current density becomes, simply,

$$J_R = \frac{2W_{||}}{BR} \qquad (32)$$

Since $\hat{e}_R$ is directed toward the Earth, and $\mathbf{B}$ is northward, the guiding center of a positive particle will drift toward the west, and the guiding center of a negative particle will drift toward the east. A westward current results in either case.

3. Diamagnetism

If a plasma is embedded in a magnetic field, the spiraling particles reduce the magnitude of the field locally. Consider the direction of motion of the charged particles. The Lorentz force produces tiny current loops whose field, interior to the loop, is opposed to the primary field. This is merely an application of Lenz's law. The orientation of all current loops, each of magnetic moment, $\boldsymbol{\mu}$, causes the plasma to acquire a dipole moment per unit volume, $n\boldsymbol{\mu}$. The magnetization of the plasma produces a macroscopic magnetic field which alters the field which was present in the absence of the plasma. In fact, the plasma tends to expel the field lines from its interior, a general property of magnetic materials which is called *diamagnetism.* Although diamagnetism is caused by the induced alignment of the dipole moments of the constituents, it is often convenient to describe the induced field in terms of equivalent, fictitious macroscopic currents. This is a common procedure in studying the properties of magnetic materials in classical electromagnetic theory.

Inside a magnetic medium, the equation relating the magnetic induction, B, and magnetic intensity, H, is generalized:

$$\mathbf{B} = \mu_M\mathbf{H} = \mu_0(\mathbf{H} + \mathbf{M}) \qquad (33)$$

$\mathbf{M}$ is the magnetization, the dipole moment per unit volume of the material. Hence,

$$\mathbf{M} = n\boldsymbol{\mu} \qquad (34)$$

The magnetostatic form of Ampere's law is

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{35}$$

Since

$$\mathbf{H} = \frac{\mathbf{B}}{\mu_0} - \mathbf{M} \tag{36}$$

$$\nabla \times \mathbf{B} = \mu_0 (\mathbf{J} + \nabla \times \mathbf{M}) \tag{37}$$

According to this equation, the origin of the B field is not only a real current but a spatial distribution of magnetization. Since $\nabla \times \mathbf{M}$ is equivalent to a current, we may introduce a fictitious current density, J_M, called the Amperian current density, where

$$\mathbf{J}_M = \nabla \times \mathbf{M} = \nabla \times n\boldsymbol{\mu} = -\nabla \times \frac{W\perp}{B}\hat{e}_B \tag{38}$$

Two simple examples may help clarify these concepts. An example which occurs frequently in treatises on electromagnetism is the case of a diamagnetic cylinder of circular cross section placed in a uniform field. Figure 8 shows a cross section through the rod. The elementary current loops are oriented with their axes along the direction of the applied field. The effect of the magnetization can be studied heuristically without resorting to equations. If one sums the currents in the interior of the rod, the result is $J_M = 0$, since adjacent to each element of a given current loop there is an oppositely directed current element. Thus, the *volume current density* is zero. However, on the surface of the rod, the current elements add constructively to produce an equivalent *surface current.*

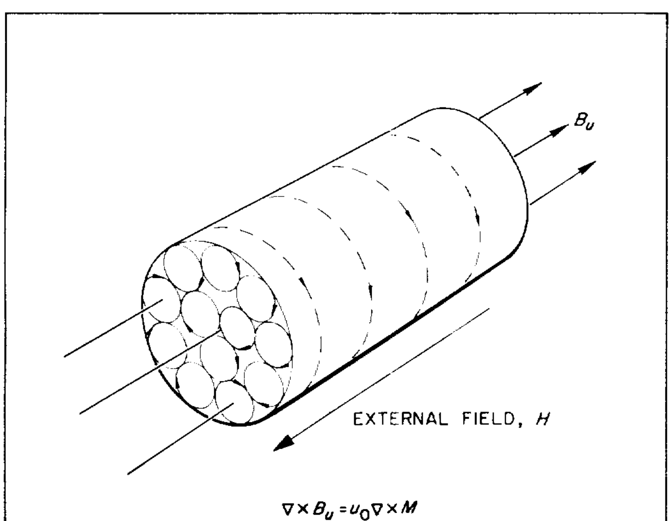

Fig. 8. Diamagnetic currents on the surface of magnetic cylinder in an external field

The magnetic effects of the rod can be determined, both inside and outside, from the field of the Amperian, surface current.

A closely related example, which is more pertinent to the present discussion, is the case of a cylindrical slab of plasma in a magnetic field. For simplicity, we assume that the field is uniform and that the plasma is a uniform, cylindrical disc, sharply bounded on both sides (Fig. 9).

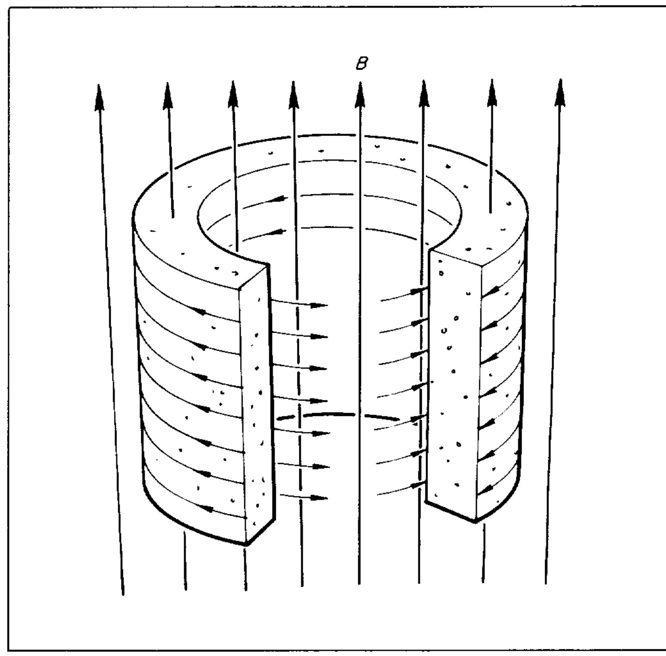

Fig. 9. Diamagnetic currents on the surfaces of a cylindrical plasma slab in an external field

Then

$$J_M = \frac{\frac{1}{2}mv^2}{B}\frac{\partial n(r)}{\partial r}\hat{e}_\phi \tag{39}$$

J_M vanishes inside the plasma, since n is constant. However, near the boundaries neither $\partial n/\partial r$, nor J_M, is zero. In effect, there are two oppositely directed current sheets on the surfaces of the plasma.

If the direction of the field is north, then the innermost surface current is eastward, and the current on the outer surface is westward. Thus, the magnetization currents cause fields which reduce the primary field interior to the plasma and which increase the primary field exterior to the plasma. The field lines have, in effect, been partially expelled by the diamagnetic plasma.

Since this example is related to the problem of the geomagnetic ring current, there are two additional comments which are worth making. If the surface currents are equal in magnitude, as in this example, the resultant field interior to the plasma ring will be increased above its value in the absence of the plasma. Consider two elements of each surface current, i.e., two filamentary current loops. The field at the center of each loop is given by

$$\triangle B = \frac{\mu_0 i}{2a} \tag{40}$$

where i is the current, and a is the radius of the ring. If $i_1 = i_2$, the field on the inner boundary will dominate since $a_1 < a_2$. Hence, to produce the main phase decrease, the westward component of the ring current must be dominant, although eastward currents may occur locally. The second comment is that, contrary to this special case, J_M will not vanish, in general, inside the plasma, and *volume diamagnetic currents* will also flow.

The current density of the ring current is the algebraic sum of these three toroidal components. Hence,

$$\mathbf{J} = \mathbf{J}_\mu + \mathbf{J}_R + \mathbf{J}_M = -\frac{W\perp}{B^2}\nabla B \times \hat{e}_B - \frac{2W||}{RB^2}\hat{e}_R \times \mathbf{B} - \nabla \times \frac{W\perp}{B}\hat{e}_B \tag{41}$$

The production of the main phase decrease by a diamagnetic ring current raises questions concerning the possible trapping of solar particles in the geomagnetic field. Modern ring current theory also has important consequences associated with the recovery phase of a magnetic storm. Presumably the recovery phase is due to the gradual dissipation of the ring current, which implies a diminished particle energy. (Note that all three components of the current density depend essentially on the energy of the trapped particles.) Dessler and Parker suggested that the ring current particles are protons and are removed by exchanging their charge with neutral hydrogen atoms (Ref. 22). This process (charge exchange) transforms an energetic proton and a thermal (low energy) hydrogen atom into an energetic hydrogen atom and a low-energy proton. Hence, energy is removed from the ring current. There is some evidence that neutral hydrogen is an important constituent of the outer atmosphere. The time required to remove a significant fraction of the energy in the ring current, based on the charge-exchange interaction cross section and theoretical density distribution of neutral hydrogen, appears to be consistent with the one-to-two-day recovery period of storm. Originally, Singer had suggested that protons responsible for the storm ring current are removed from trapped orbits by interaction with the Earth's atmosphere near their "mirror points" (Ref. 20). Normally, only particles having a narrow range of pitch angles penetrate deeply enough into the atmosphere to lie inside such a "loss cone." In order to remove particles continuously, Singer postulated that some mechanism exists, such as scattering by charged particles or hydromagnetic waves, which leads to a steady redistribution of particle pitch angles.

At the present time, modern ring current theory seems to be based on sound physical principles. The modern theory explains the maintenance of the ring current in a satisfactory way and with a minimum number of assumptions. If plasma becomes trapped in the geomagnetic field, a ring current must exist. The theory relates the current density of the ring current to the properties of the trapped plasma. The same equations have also been derived recently in connection with thermonuclear research. Thus, they represent general results of modern plasma physics (Ref. 27).

E. Modern Ring Current Theory: Numerical Results

There have been several theoretical investigations of the ring current associated with an assumed number density distribution function of trapped particles, n. Given n, and the characteristics of the geomagnetic field, the total current density can be derived from Eq. (41). The perturbation field, $\triangle B$, produced by the current distribution can be computed from J, using the Biot-Savart law. Determination of the perturbation field involves an integration over the entire volume of the current for each individual point of observation. The integrals have been evaluated numerically using electronic computers. Akasofu and Chapman, and Apel, Singer, and Wentworth, have carried out this type of calculation (Eq. 28 and 29). The theoretical disturbance field, $\triangle B$, and resultant field, $G + \triangle B$, were computed for points of observation in the magnetosphere as well as at the surface of the Earth. The calculations can be compared with magnetic field measurements made by spacecraft magnetometers. Since the results of such measurements will be presented and discussed in Part II, it will be helpful to review briefly the most pertinent results of these calculations before proceeding to a study of the data.

In general, the density distribution function, n, will depend on (1) position, such as geomagnetic latitude and geocentric distance, (2) the pitch angle of the particles, usually specified by its value as the particle crosses the equatorial plane (the pitch angle is the inverse tangent of $V\perp/V_{||}$), and (3) the kinetic energy of the particles. In the models to be discussed, the expression for n was simplified by assuming (1) that the particles all have the same average energy, E_0, and (2) that n can be represented as the product of two functions, a term, Nr_e, which specifies the radial dependence along the equatorial plane, and a term which essentially determines the pitch angle distribution. The results appear to depend primarily on the radial dependence of n, and to a lesser extent on the pitch angle distribution. Hence, in the following, we will characterize n by Nr_e. The interested reader is referred to the literature for the exact details of the mathematical description.

Figure 10 contains the results of the Akasofu-Chapman and the Apel-Singer-Wentworth calculations. The numerical calculations were carried out for points of observation in the equatorial plane because of the simplifications associated with latitudinal symmetry. The radial density distribution functions appear in Fig. 10a. Figure 10b shows the current density function corresponding to each. Negative values correspond to eastward currents and positive values to westward currents. Figure 10c shows the perturbation field on the equatorial plane as a function of geocentric distance. The perturbation field is southward inside the ring current in spite of the contribution from the diamagnetic, eastward current component. The field minimum occurs at the peak in the particle distribution function. This illustrates the basic diamagnetism of the plasma. Exterior to the ring current, the field is northward and increases the field magnitude above that of the unperturbed dipole field. Figure 11 is a plot of the total magnitude of the resultant field on the equatorial plane. The Earth's dipole field is also shown for comparison.

Figure 11 reveals an important difference between the Apel-Singer-Wentworth and Akasofu-Chapman calculations. The perturbation field derived by the former does not lead to a reversal of the Earth's field gradient. In the Akasofu-Chapman results, however, there is a region, just beyond $6Re$, where the Earth's field increases rather than decreases, i.e., the Earth's field gradient is reversed. It is possible to obtain a result which contradicts some of the

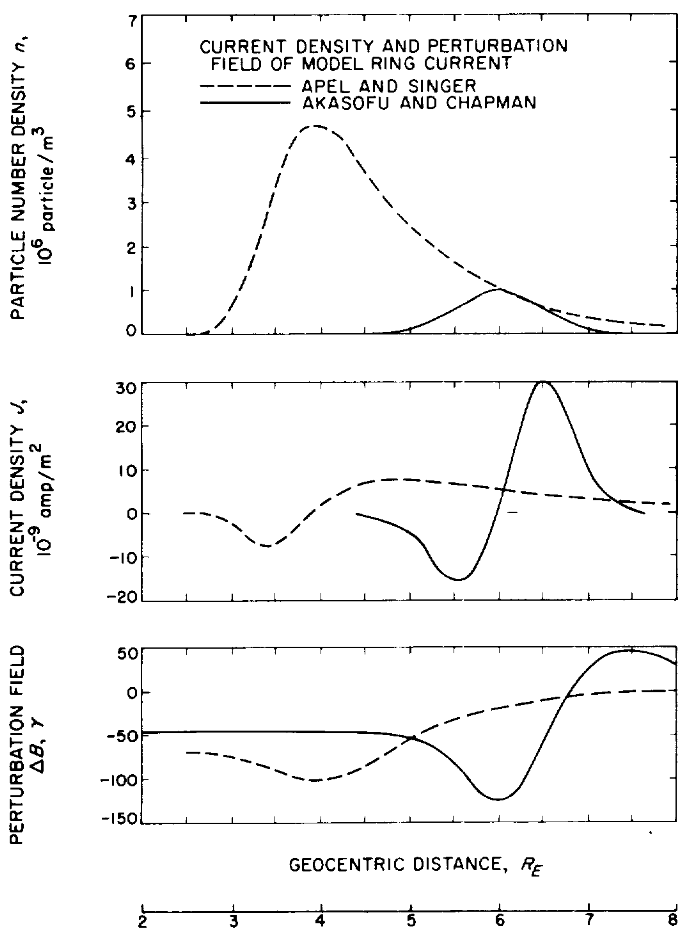

Fig. 10. The ring current and perturbation field of a model trapped particle distribution

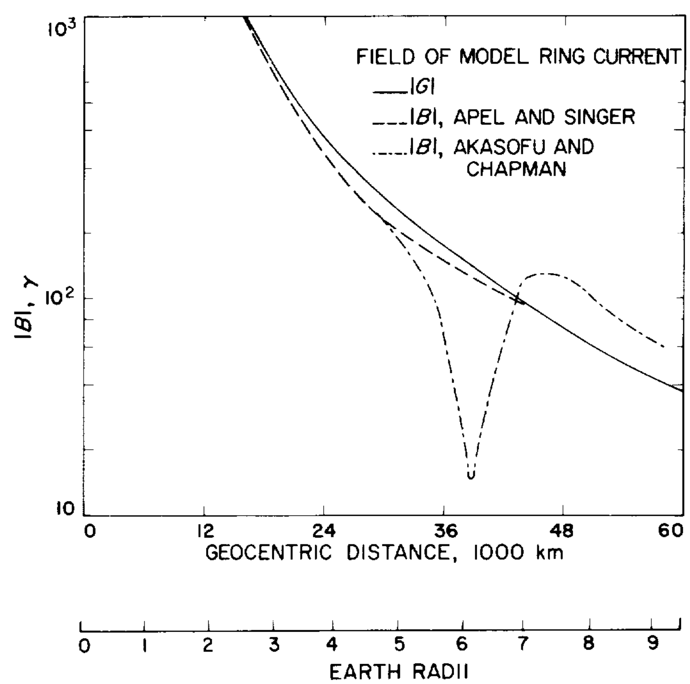

Fig. 11. The resultant field of a model ring current compared with the geomagnetic field

fundamental premises because this type of calculation is not self-consistent. The ring current field can significantly perturb the geomagnetic field so that it is not legitimate to determine J solely from the characteristics of the dipole field. This approach can only provide a first approximation to the exact solution. Although the Apel, Singer, and Wentworth ring current does not lead to a reversal of the Earth's field gradient, they show that there is a self consistent solution in which it is, indeed, reversed so that either of the above field configurations is possible.

III. THE EXISTENCE OF THE RING CURRENT: EXPERIMENTAL EVIDENCE

A. *Evidence Based on Surface Observations*

Particle and field measurements at the Earth's surface provide indirect evidence for the existence of a ring current. The evidence is based on (1) the harmonic analysis of the main phase, storm field, (2) the changes in the geographic location of aurora during magnetic storms, (3) the arrival of solar protons at "forbidden" latitudes during storms, and (4) the observation of a cosmic ray "latitude knee."

The geographic dependence of the magnetic storm field has been studied extensively. These studies show that the storm field can be divided into two parts. One component, S_D, the disturbance daily variation, is a function of local time. The other component, D_{st}, the storm time variation (see Fig. 2 and the description of the storm phases), is independent of longitude, or local time. The D_{st} variations are a world-wide effect and occur simultaneously over the entire surface of the Earth. Simultaneous observations at ground stations which are well distributed in latitude and longitude make it possible to expand the D_{st} field into a series of spherical harmonic functions. Harmonic analysis has shown that the D_{st} field must be an overhead current system, i.e., above the Earth's surface. The altitude at which the current system is located is not uniquely established by such an analysis. Chapman derived a possible current system consisting of concentric current loops lying on a spherical surface just above, and completely enclosing, the Earth (Ref. 30). However, as Chapman pointed out, a toroidal ring current at much greater altitudes could produce the same D_{st} field at the Earth's surface.

During magnetic storms, the location of the polar aurora shifts to lower geomagnetic latitudes (i.e., $< 68°$). Bless, Gartlein, Kimball, and Sprague have derived an empirical relation between the latitude of the auroral maximum and the magnetic K index (Ref. 6). As we have seen, Stoermer proposed that such observations were caused by the effect of an extraterrestrial ring current on the trajectories of solar particles incident on the Earth from interplanetary space. Even if the origin of the auroral particles should turn out to be the radiation zones, or some other reservoir of trapped particles, the shifting of the aurorae is likely to be the result of a large-scale deformation of the distant geomagnetic field, which could be caused by a ring current.

There is another observation which appears to be explainable by Stoermer's analysis. Kellogg and Winckler have recently discussed observations of solar protons by balloon-borne equipment flown near Minneapolis, Minnesota (Ref. 7). The balloon data shows that 75 Mev protons emitted by the Sun are able to enter the atmosphere during the beginning of the main phase of magnetic storms. Protons in this energy range would normally be forbidden at such latitudes. Kellogg and Winckler suggest that this effect is due to the formation of the main phase ring current.

There are certain characteristics of cosmic radiation which are also consistent with the existence of the ring current. The experimental measurements of cosmic ray intensity exhibit a latitude dependence. Beginning at low latitudes the intensity increases with increasing latitude. This result is predicted by Stoermer's theory since the low-energy cosmic rays are able to reach the Earth's surface only at the higher latitudes. However, a latitude is reached at which the intensity ceases to increase. Cosmic ray physicists have chosen to call this feature the "knee" in the intensity versus latitude curve. This observation could imply that the primary cosmic radiation has a low-energy cutoff. However, Ray has shown that the observations are consistent with the effects of a ring current, located at 7.5 R_E, having a magnetic moment equal to that of the Earth (Ref. 31). He also showed that an apparent variation in the latitude of the "knee" with the solar cycle is consistent with a diminution of the ring current during the solar minimum.

Although the above observations are consistent with the existence of a ring current, all that surface observations really imply is that the Earth is immersed in a large scale disturbance field. The origin of such a field is very difficult, if not impossible, to ascertain from surface observations alone. This explains the importance of investigating the nature of the disturbance field above the Earth's surface using satellites and space probes.

B. Evidence from Spacecraft: Field Measurements

Because of the recent development of rocket technology, it is now possible to make direct measurements of the distant geomagnetic field. Magnetic field measurements, or simultaneous field and particle measurements, should definitely establish the presence or absence of the geomagnetic ring current. The following discussion is a summary of the measurements carried out on spacecraft as they pertain to this question of the existence of the ring current.

At the present time, seven spacecraft have carried magnetometers into the distant geomagnetic field. Table 1 contains the spacecraft name, or designation, and the respective launch dates. The table also indicates whether the spacecraft was a probe or satellite, an important distinction, since a space probe, obviously, makes a single

Table 1. Spacecraft containing magnetometers

Spacecraft designation	Date	Type of spacecraft	Magnetic conditions at the Earth's surface
Pioneer 1	October 11-12, 1958	space probe	one of 5 quiet days
Lunik 1	January 2, 1959	space probe	one of 5 quiet days
Explorer 6	August 7 to September 16, 1959	Earth satellite	magnetic storms: Aug. 16 and Sept. 3
Lunik 2	September 12, 1959	lunar impacter	one of 10 quiet days
Vanguard 3	September 18 to November 12, 1959	Earth satellite	magnetic storms: Sept. 19 to 21
Pioneer 5	March 11, 1960	space probe	one of 5 disturbed days
Explorer 10	March 25-27, 1961	Earth satellite	quiet until storm: March 27

traversal of the Earth's field, while a satellite makes periodic measurements under a variety of magnetic conditions. Finally, Table 1 indicates the magnetic conditions at the Earth's surface during the measurements. (An international organization tabulates the five most quiet, ten most quiet, and five most disturbed days of each month.) Figure 12 shows the essential orientation of the probe trajectory or satellite orbit with respect to the Earth-Sun direction. The orientation of *Pioneer 3* and *4* are also included, since these spacecraft will be referred to in connection with charged particle measurements.

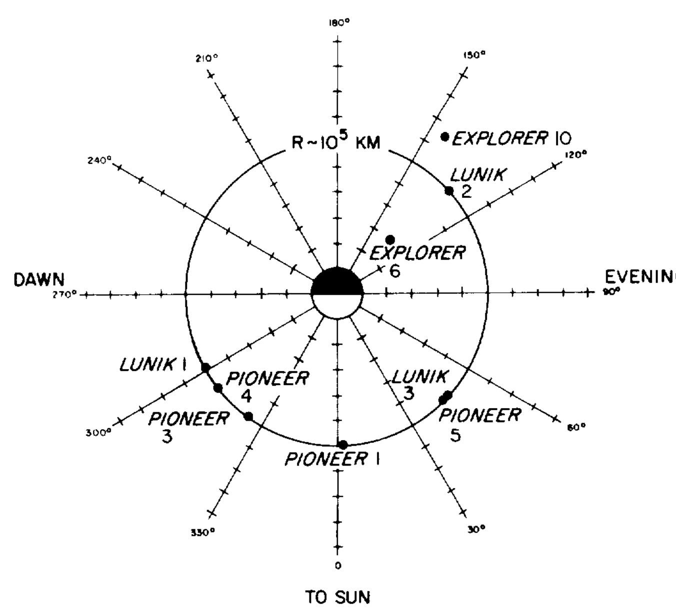

Fig. 12. Spacecraft orientation referred to the Earth-Sun direction

1. Pioneer 1 (Sonett, Judge, Sims, and Kelso)

Pioneer 1 contained a search coil magnetometer consisting of a solenoid wound on a high permeability core and a voltage amplifier tuned to the rotation frequency of the spin-stabilized spacecraft. The output voltage from the search coil amplifier is a sinusoid whose amplitude is proportional to the ambient magnetic field projected into the equatorial plane of the spacecraft (i.e., perpendicular to the spin axis). The projected field magnitude is called $B_\perp$.

Figure 13 is a plot of the *Pioneer 1* measurements of $B_\perp$ as a function of geocentric altitude (Ref. 32). A latitude dependence is also implicit since the trajectory was not confined to an equatorial plane. (This condition is also characteristic of the trajectories of all satellites and space probes discussed below.) Also shown in Fig. 13 is, $G_\perp$, the corresponding value of the geomagnetic field extrapolated from the surface to the position of the spacecraft. The extrapolation is based on a spherical harmonic expansion of the surface field. The geomagnetic field, rotated into the spacecraft frame of reference, has a component perpendicular to the spin axis, $G_\perp$. The observed field can be compared with the theoretical value of the geomagnetic field at great altitudes. A large scale departure between the two could indicate the presence of a ring current.

Pioneer 1 data was obtained in the region from 3.7 to 7 R_E. Because of instrumental difficulties which led to an uncertainty in the calibration of the magnetometer, it was necessary to normalize the data. $B_\perp$ was made to equal $G_\perp$ at 3.7 R_E. The rest of the data points were then found to agree quite well with the Earth's dipole field. The *Pioneer 1* data were obtained during an interval of very quiet magnetic conditions at the surface.

2. *Luniks 1* and 2 (Dolganov and Pushkov)

The *Lunik 1* magnetometer was a tri-axial fluxgate magnetometer. It was oriented by servomechanisms so that two of the magnetometer sensors were normal to the ambient field. The signal from the third sensor, which was parallel to the field so that it measured the total magnitude, was telemetered. Data were obtained between 2 and 6 R_E while the spacecraft was moving from 30°N magnetic latitude to 15° North latitude. The data, B, are shown in Fig. 14 (Ref. 33). G, the scalar magnitude of the extrapolated geomagnetic field, is also shown as a function of geocentric altitude. There are two features of particular interest: (1) there is a general depression of the observed field such that $B < G$ everywhere, and (2) there is an anomaly, located between 3 and 4 R_E, superposed on the general field depression. The anomaly has the approximate shape of a single cycle of a sinusoid with a peak to peak amplitude of 400 γ.

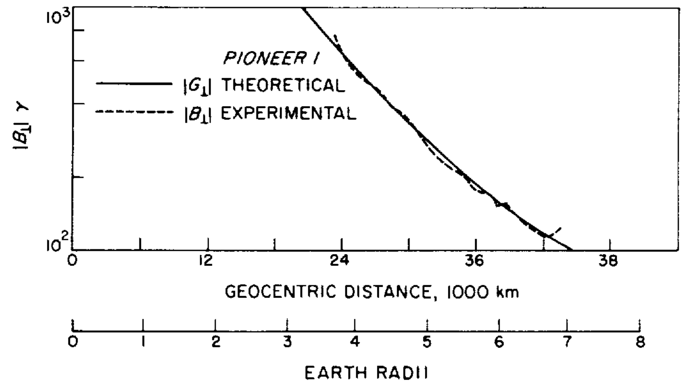

Fig. 13. *Pioneer 1* magnetometer data

The *Lunik 1* data were greeted with a great deal of interest, particularly the large-scale anomaly at 3-4 R_E. The radiation zones had been discovered only a short time before and it was known that the peak in the outer zone was located at approximately the same altitude. It was speculated that a ring current had been observed which was associated with the radiation particles.

Antsilevich and Shevnin attempted to support the hypothesis that a ring current was responsible for the anomaly by comparing the *Lunik 1* data with ground station magnetograms (Ref. 34). There was a small magnetic storm on the launch date, beginning at 1120 hr GMT and exhibiting a main phase decrease of 20 γ at 1400 hr GMT. (However, the *Lunik 1* measurements were made at 1800 hr GMT.) At the altitude for which the field lines passing through the anomaly cross the equator, a 20 γ decrease in the surface field implied a ring current of $6 \cdot 10^5$ amperes. Antsilevich and Shevnin computed the magnitude of the current required to produce a 400 γ change, on the assumption that the spacecraft passed directly through the current. The result was $5 \cdot 10^5$ amperes. Therefore, they concluded that the results did not contradict the hypothesis that there was a ring current at 3 to 4 R_E when the measurements were made.

However, critics of this interpretation were quick to point out that the data show a reversal of the Earth's field gradient. According to the generally accepted theoretical view, such a feature might not exist as a steady state. It has been suggested that the generalized depression could be the result of a ring current and that the anomaly could be a time dependent, transient phenomenon (Ref. 35). Subsequent magnetometer flights, to be discussed below, have failed to reproduce the anomaly. It does not appear to be a permanent feature of the distant field nor is it associated with the outer radiation zone.

Lunik 2 also contained a tri-axial fluxgate magnetometer. The signals from the three axes were each telemetered and the field magnitude was computed from the three components. The *Lunik 2* data are also shown in Fig. 14 (Ref. 36). There is no evidence of either the large scale depression or the anomaly which appeared in the *Lunik 1* data, at least neither is present in anywhere near the same magnitude. The *Lunik 2* data show a succession of large field fluctuations between 4 and 8 R_E. Apparently, no one has offered an explanation of these fluctuations. There is no evidence of a ring current in the *Lunik 2* data, although the large variations from 4 to 8 R_E could have obscured a moderate, large-scale departure from the extrapolated geomagnetic field.

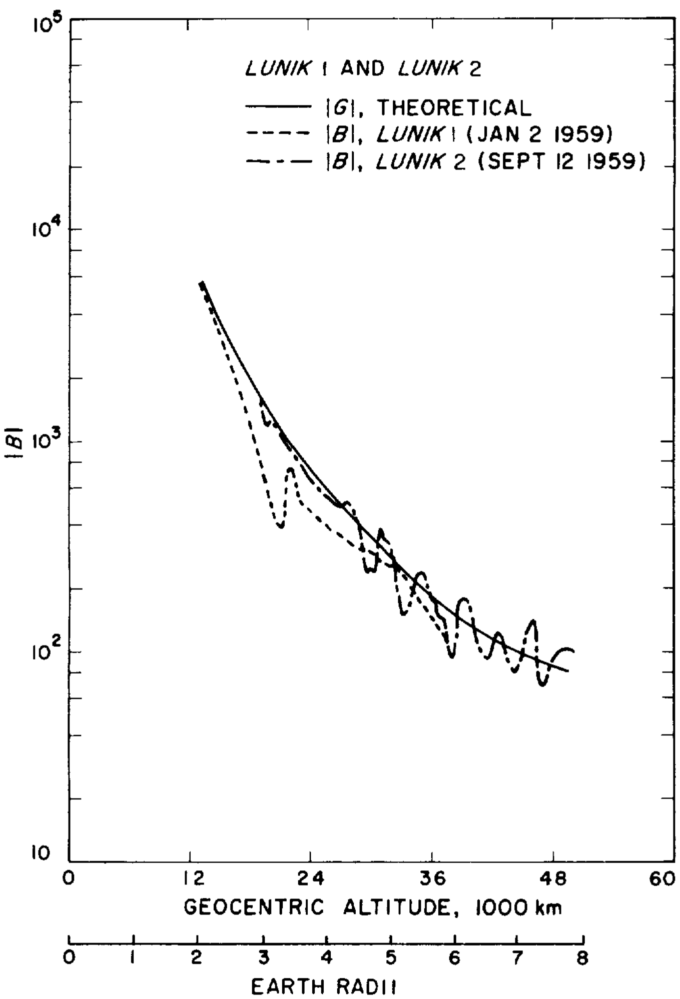

Fig. 14. *Lunik 1-Lunik 2* magnetometer data

3. **Explorer 6 and Pioneer 5** (Sonett, Judge, Coleman and Smith)

Explorer 6 contained a search coil magnetometer similar to the one flown on *Pioneer 1*. However, in addition to the magnitude of the field component perpendicular to the spin axis ($B_\perp$), the *Explorer 6* magnetometer also measured its direction. The direction of $B_\perp$ was determined by a magnetic field aspect indicator which measured the time delay between the zero-voltage crossing of the search coil sinusoid and a pulse received from a photodiode, attached to the shell of the spacecraft, when it was illuminated by solar radiation. The phase comparator measures the *phase angle*, ϕ, between $B_\perp$ and $S_\perp$, the latter being the projection into the equatorial plane of the spacecraft of a unit vector pointing in the direction of the sun (see Fig. 15). Thus, ϕ is essentially the declination of the magnetic field with respect to the Earth-Sun direction.

The *Explorer 6* orbit was highly eccentric (apogee = 48,800 km; perigee = 6740 km). The orbit plane was non-equatorial, being inclined at an angle of 47° with respect to the geographic equator. The major axis of the orbit made an angle of 20° with the equatorial plane and was turned through an angle of 135° with respect to the Earth-Sun direction, i.e., apogee was located on the side of the Earth opposite the Sun at approximately 2100 hr local time (see Fig. 12). The *Explorer 6* orbital period was 12¾ hr so that the distant geomagnetic field was traversed twice a day. Scientific data was obtained almost continuously (18 hr a day on the average) for 40 days. During that interval several magnetic storms occurred at the Earth's surface as well as several periods of magnetic quiet. The experimental results obtained during magnetically quiet and magnetically disturbed conditions will be reviewed separately.

Explorer 6 data obtained on non-storm days (Fig. 16) reveal discrepancies between $B_\perp$ and $G_\perp$ throughout most of the trajectory (Ref. 37 and 38). At altitudes below approximately 5 R_E (the actual altitude is time dependent) the observed field magnitude exhibits the same general altitude dependence as the geomagnetic field but tends to have a somewhat larger magnitude. Beyond 5 R_E, $B_\perp$ differs from $G_\perp$ in both magnitude and altitude dependence. The phase data indicate close agreement between ϕ and ϕ_G out to 5 R_E where, again, a deviation of ϕ from ϕ_G typically occurs.

The *Explorer 6* data indicate that the extraterrestrial field is essentially dipolar out to 5 R_E but that there is a large scale deviation which becomes progressively larger

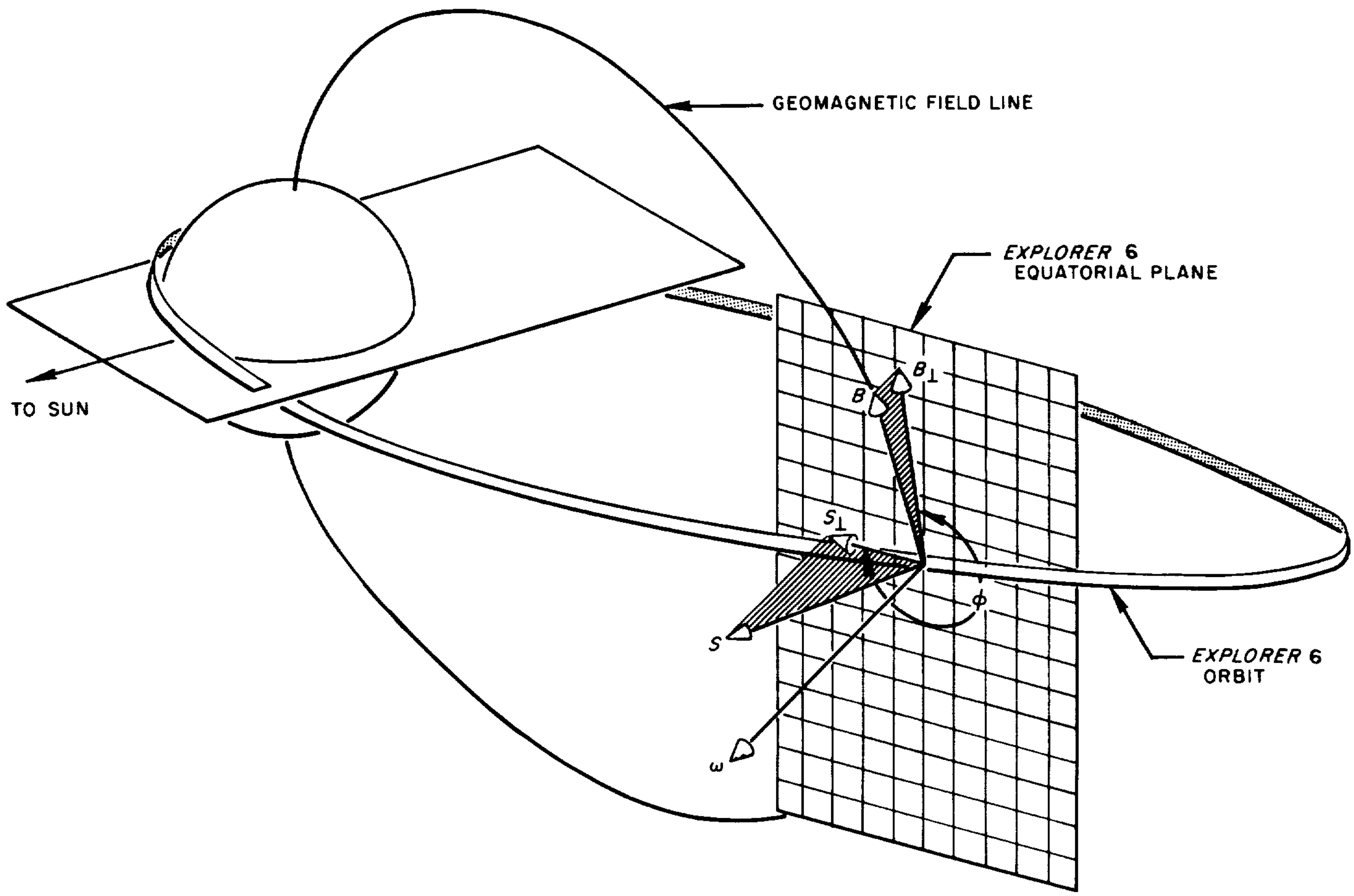

Fig. 15. *Explorer 6* spacecraft coordinates

at greater altitudes. The existence of the deviation is evidence of a large scale current system in the magnetosphere.

An attempt was made to determine the characteristics of the current responsible for the observed deviation. The shapes of the magnitude difference, $B_\perp - G_\perp$, and phase difference, $\phi - \phi_G$, are strongly dependent on the geometry of the experiment, particularly the spacecraft trajectory and spin axis orientation. Model calculations were employed to overcome the geometrical effects as well as to investigate the characteristics of the current. A simple mathematical model of the current was used, i.e., a longitudinal current with a finite, circular, cross-sectional area. The field due to the current was computed at points along the trajectory, added vectorially to the geomagnetic field, and a coordinate transformation was performed to yield $B_\perp$ and ϕ. Figure 17 shows a comparison of the data and the results of the model calculation (Ref. 39). Reasonable agreement was obtained for a westward current of 5.10^6 amperes located at 10 R_E. According to the model calculations, *Explorer 6* did not penetrate into the current which implied that the cross-sectional radius of the current had a value less than 3 R_E.

At the time these results were obtained, magnetometer data became available from *Pioneer 5*, which contained a search coil magnetometer similar to the one flown on *Explorer 6*. (However, no phase data were available.) While the *Explorer 6* orbit was directed away from the Sun, *Pioneer 5* passed through the distant geomagnetic field on the sunward side of the Earth. The same mathematical model was applied to the *Pioneer 5* data, which was digitized before being telemetered (Fig. 18). Reasonable agreement was obtained between the data and the model calculations for a westward current of 5.10^6 amperes, located between 5 and 11 R_E (Ref. 39). The similar current characteristics in the two regions of space suggests that the deviation is caused by a ring current. August 9, 1959 *(Explorer 6)* was somewhat disturbed but

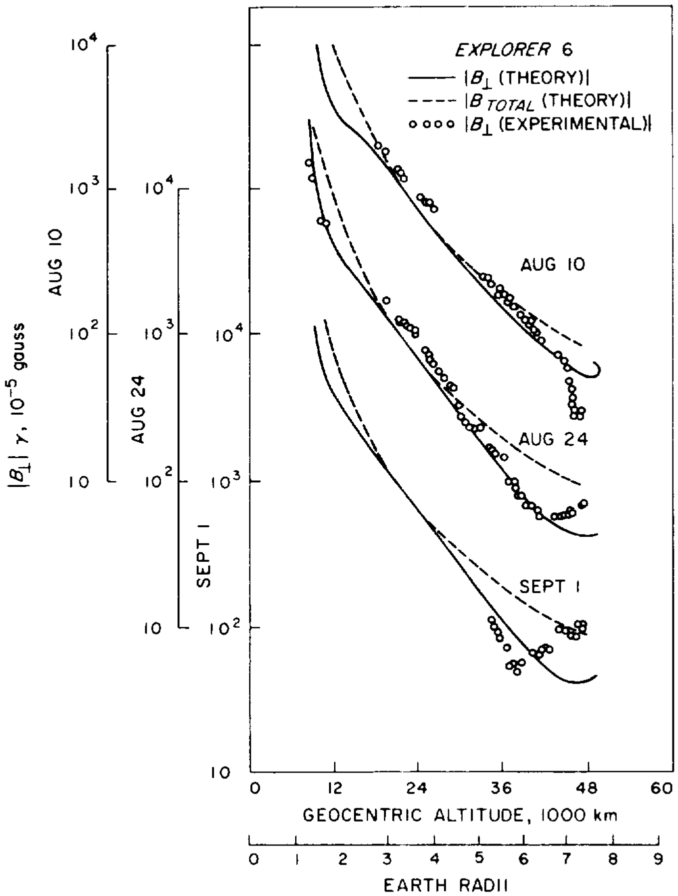

Fig. 16. *Explorer 6* magnetometer data

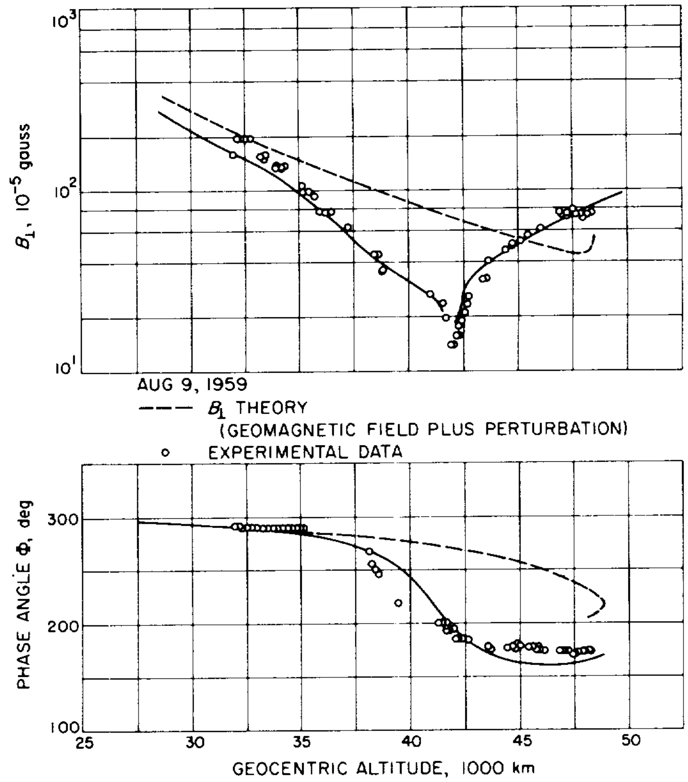

Fig. 17. *Explorer 6* magnetometer data and model calculations

was not actually a storm day. March 11, 1960 (*Pioneer 5*) contained a moderate magnetic storm.

Explorer 6 data obtained during magnetic storms will now be discussed (Ref. 40). Figure 19a is the time variation of the field magnitude in the outer radiation zone for points of observation near the geomagnetic equatorial plane. Each datum is obtained from the average field magnitude, $B_\perp$, at an altitude of approximately 24,000 km (3.75 R_E) during a single orbital pass. Figure 19a is a plot of $B = B_\perp - G_\perp$ during the first two weeks of *Explorer 6* observations.

This time interval contained the severe magnetic storm of 16 August. Figure 19b shows the time variation of the horizontal component of the Earth's field at the surface. Each datum is the variation in the daily mean value of the horizontal intensity at Huancayo, Peru (geomagnetic latitude, $-0.6°$) normalized to the two quiet days, August 11 and 12. The Huancayo data show the effect of three superimposed magnetic storms during August 15 through 20. Figure 19c is a smoothed D_{st} curve and shows the characteristics of the severe, sudden-commencement storm of August 16 in greater detail (Ref. 41).

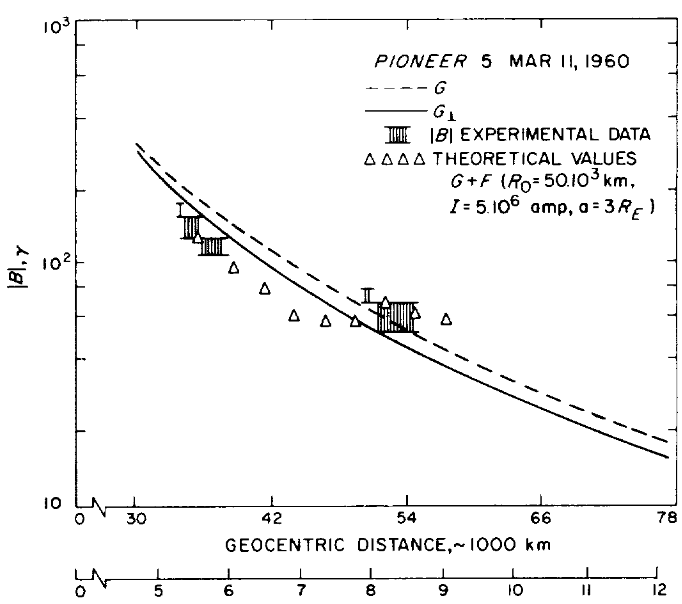

Fig. 18. *Pioneer 5* magnetometer data and model calculations

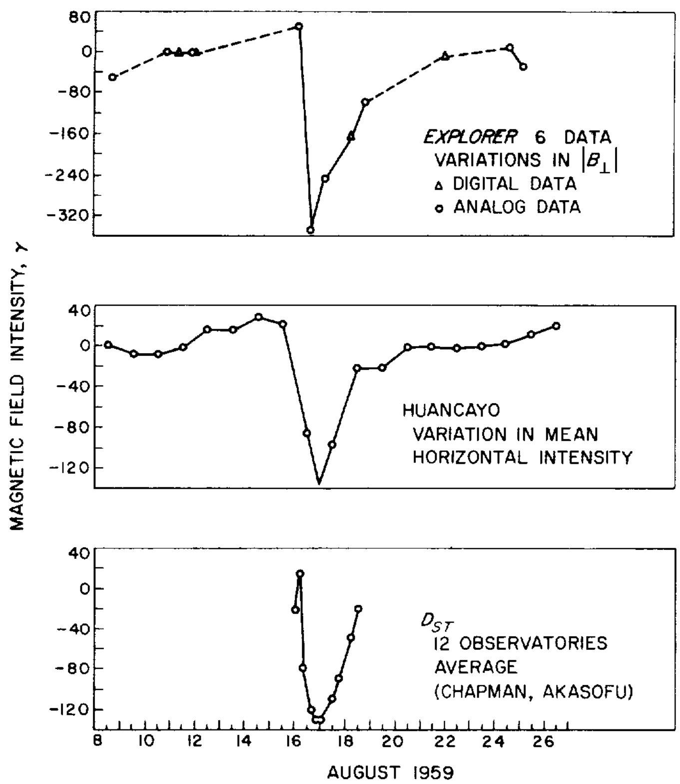

Fig. 19. Magnetic storm variation in the field magnitude near $4R_E$ and at the Earth's surface

The orientation of the *Explorer 6* spin axis was such that $G_\perp$ was approximately equal to G at the particular altitude, 4 R_E. If the storm perturbation field is (1) symmetric above and below the equatorial plane and (2) confined to magnetic meridian planes defined by the dipole field lines and the center of the Earth, then B should represent the time dependence of the disturbance field on the equatorial plane. The latter point of observation is important because only the magnitude of the geomagnetic field would be affected by a ring current without a corresponding change in direction. (The storm field is anti parallel to G on the equator.) Furthermore, most of the theoretical calculations involving diamagnetic ring currents have been restricted to the equatorial plane.

Figure 19 shows that the long period variation of the storm field at the surface (D_{st}) is reproduced at an altitude of 4 R_E. There is a main phase decrease and recovery phase at 4 R_E which is coincident with D_{st}. The magnitude of the main phase decrease is 360 γ at 4 R_E and 140 at the surface, i.e., it is approximately two and one half times larger. Furthermore, the direction of the storm field is the same at one and four Earth radii, i.e., opposed to the geomagnetic field.

The interpretation of the experimental data is simplest for points of observation located on the geomagnetic equatorial plane. At non-zero latitudes the vector sum of the disturbance field and the geomagnetic field will cause changes in the direction of the distant field, as well as changes in magnitude. Changes in direction can be studied by considering the phase angle data.

Figure 20 shows the departure of the observed field direction (ϕ) from the direction of the extrapolated geomagnetic field (ϕ_G) and contrasts the departure on storm days and days that are magnetically quiet. There were magnetic storms on August 17 and September 4, while August 27 was the quietest day of the month.

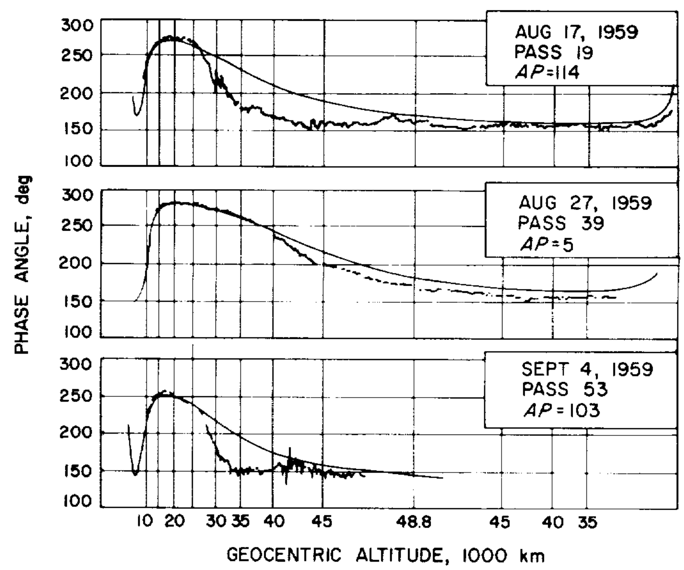

Fig. 20. Field direction during two storm days and a quiet day

When the variation in ϕ is studied throughout a given magnetic storm, it is found that there is a progressive enhancement of $\triangle\phi$ during the storm with a subsequent, gradual return to the pre-storm values. Figure 21a shows the variation in $\triangle\phi$ at an altitude of 40,000 km during the August 16 storm. Figure 21b contains the simultaneous variation in the horizontal intensity at the Earth's surface (hourly mean values at Huancayo) and Figure 21c is a plot of the corresponding 3-hr K index (which is a measure of the magnitude of the field fluctuations at the surface). The direction of the distant field is correlated with both the variations in the horizontal component, and with the degree of the magnetic agitation of the surface field.

The *Explorer 6* storm data imply that the main phase decrease is only one manifestation of a very large scale magnetic field which surrounds the Earth. This much of the original speculation out of which the concept of the ring current evolved appears to be true. Furthermore, the storm field seems to represent an enhancement of a large scale disturbance field which can exist during quiet intervals.

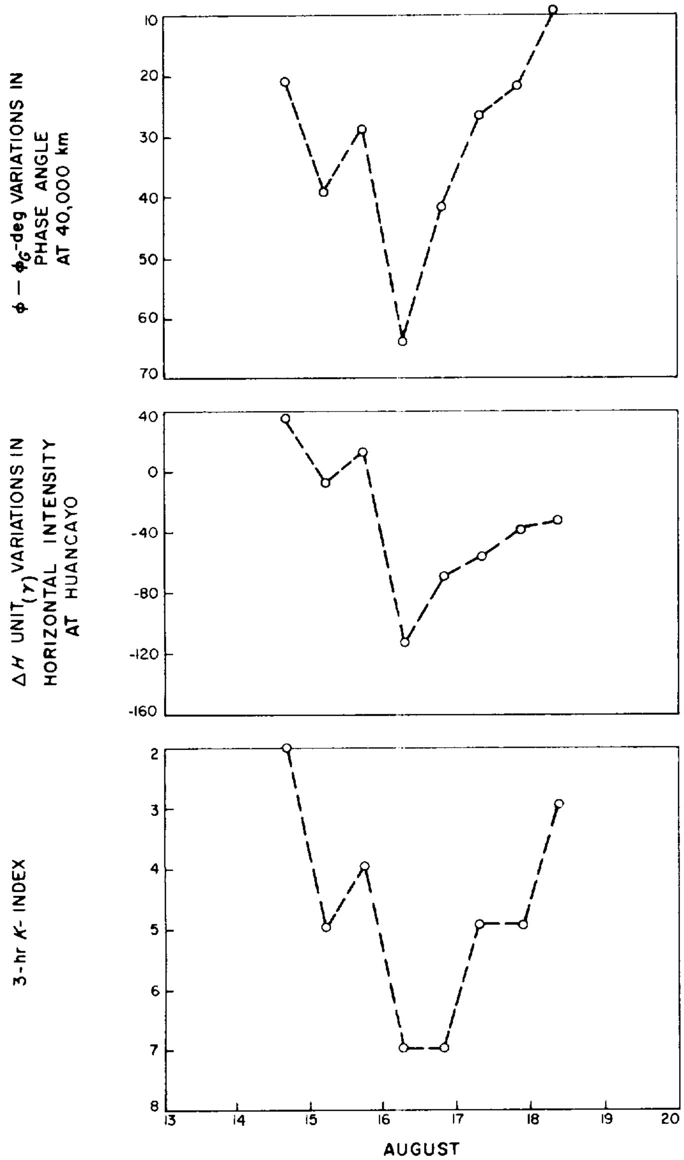

Fig. 21. Magnetic storm variation in field direction at $6.25R_E$ compared with variations in the surface field

The *Explorer 6* data also imply that the geomagnetic field dominates the storm field out to at least 8 R_E. The evidence is the following: (1) the gradual time variation from quiet to disturbed conditions and the subsequent recovery, (2) the correlation with the slow storm variations of the surface field, and (3) the existence during the storm main phase of trapped radiation particles on lines of force which cross the equator near this altitude (Ref. 42). The dominance of the geomagnetic field is an important condition, if the large scale field is to be explained by a diamagnetic ring current of the type discussed above. Since G is 60 γ at 8 R_E on the equatorial plane, it follows that D, the disturbance field, must be less than 60 γ. Since the disturbance field is -100 γ at the Earth's surface and -360 γ at 4 R_E, this implies a rather strong variation of the disturbance field with altitude (see Fig. 22).

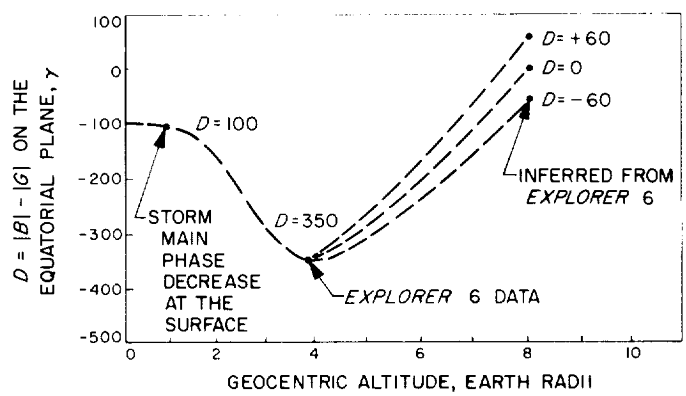

Fig. 22. Magnitude of the storm field near the equatorial plane inferred from surface and *Explorer 6* measurements

In general it has not been possible, thus far, to get good quantitative agreement between the storm data and simple current models (e.g. the longitudinal current with finite circular cross section or a circular loop). Good agreement has been obtained for specific orbits. However, the current required to fit the data at 5 - 8 R_E does not account for all of the main phase decrease at the surface. In spite of such ambiguities, which may reflect the inadequacies of the simple models, the storm data is clearly qualitatively consistent with the existence of a ring current. Model calculations had previously demonstrated this for non-storm days.

4. *Vanguard 3* (Heppner, Stolarik, Cain, and Shapiro)

The earth satellite, *Vanguard 3*, contained a proton-precession magnetometer which measured the total, scalar magnitude of the geomagnetic field, G. *Vanguard 3* was placed in a low-altitude orbit (perigee 6880 km and apogee 10,120 km). This orbit was chosen in order to carry out an extensive mapping of the Earth's field above the ionosphere. Data were obtained once per orbit for a period of nearly two months. The data indicated that the field magnitude was systematically less by 100 γ than was anticipated on the basis of extrapolated spherical harmonic expansions (Ref. 43). Taken at face value, this implies that either (1) the usual field expansions are incorrect or (2) that there is a current system above the satellite orbit. Data obtained during several, moderate magnetic storms showed that the field magnitude above the ionosphere tended to be reduced during the storm main phase. This result agrees with the *Explorer 6* data and is consistent with a westward storm current above the satellite orbit.

5. *Explorer 10* (Heppner, Ness, Skillman, and Scearce)

Explorer 10 was placed in a highly eccentric orbit (apogee 46.5 R_E). Technically, it was an Earth satellite. However, data could only be obtained on the outward portion of the first orbit during 53 hr of equipment operation. Therefore, the information it provided is similar to that obtained with space probes. The spacecraft contained both a fluxgate and a rubidium magnetometer. The latter was used to measure the total magnitude of the geomagnetic field near the Earth ($R \leqslant 7\ R_E$) and to calibrate the fluxgate magnetometers at higher altitudes.

The data obtained below 7 R_E are shown in Fig. 23 (Ref. 44). There is a discrepancy of only tens of gamma between B and G, which apparently cannot be attributed to uncertainties in the spacecraft trajectory. The depressed value of the field ($\triangle B < 0$) agrees with the *Vanguard 3* results. The experimenters suggest that there is a current located in the slot between the inner and outer radiation zones which causes these discrepancies. The surface field prior to, and during launch, was magnetically quiet.

At altitudes beyond 7 R_E, the fluxgate magnetometers gave both the magnitude and direction of the distant field. The latter is expressed in terms of two angles, ψ, the Sun-phase angle discussed in connection with *Explorer 6*, and α, the angle between B and the spacecraft spin axis.

Figures 24 and 25 contain B, α, and ψ as a function of geocentric distance over the range from 4 to 20 R_E. The geomagnetic field is strongly deformed throughout this region. B is greater than the Earth's dipole field and shows a clockwise rotation of field direction (the spacecraft was located at southern magnetic latitudes). These observations are qualitatively consistent with the *Explorer 6* data, particularly the sense and magnitude of the field rotation. Apogee for both *Explorer 6* and *Explorer 10* occurred at an angle of ~135° with respect to the Earth-Sun direction at southern latitudes so that the orbits bear

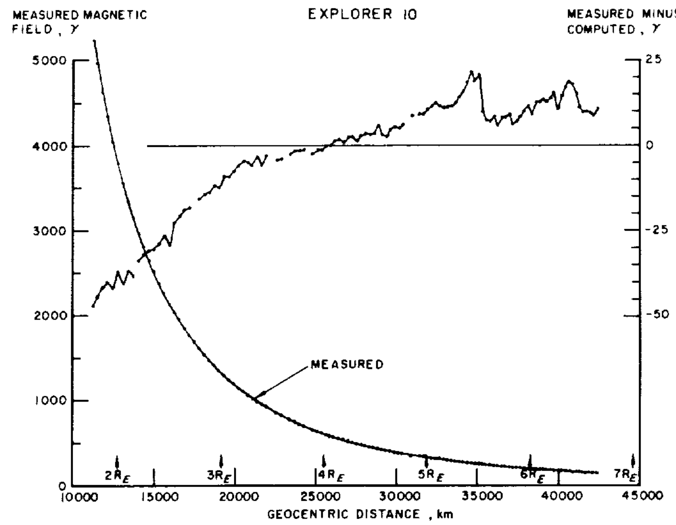

Fig. 23. *Explorer 10* magnetometer data at radial distances of less than 7R_E

a certain resemblance to one another. Similarly, *Pioneer 1* and *Pioneer 5* showed a region of increased field magnitude at large distances (~ 15 R_E). However, they passed through the Earth's field on the sunward side and the magnitude of the increase nowhere appeared to be more than double the value of the unperturbed geomagnetic field. (The Chapman-Ferraro theory predicts that the field magnitude will be double in the vicinity of the magneto-pause.)

In their preliminary analysis of the data, the experimenters state that the field has the character of a superposition of the Earth's field and a solar-interplanetary field, although it could be the result of the geomagnetic field being swept around to the dark side of the Earth by the solar wind. They do not favor an explanation involving a ring current near or beyond 10 R_E (cf. *Explorer 6*).

C. Evidence from Spacecraft: Particle Measurements

According to modern ring current theory, the question of the possible existence of a ring current in the magnetosphere is also a question of whether or not plasma is trapped in the geomagnetic field. Conclusive evidence for the existence of the ring current probably requires the simultaneous observation of (1) a characteristic deformation of the geomagnetic field and (2) a distribution of charged particles having sufficient total energy to produce the observed field deformation consistent with the theory. The question of particle trapping is crucial, since the Stoermer theory indicates individual particles cannot be trapped unless an injection mechanism exists.

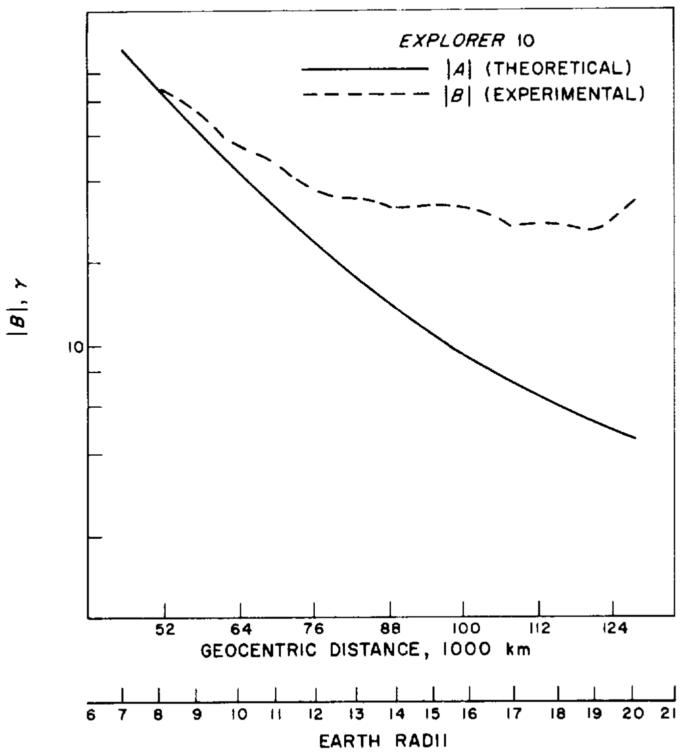

Fig. 24. *Explorer 10* magnetometer data (field magnitude) between 7 and $20R_E$

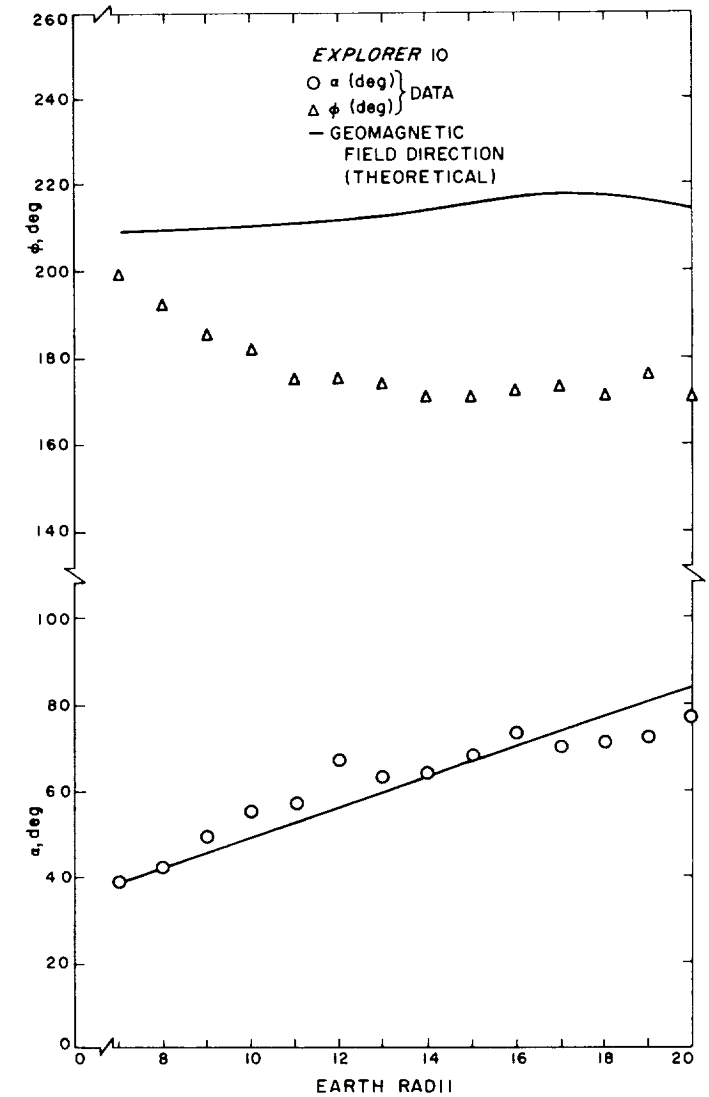

Fig. 25. *Explorer 10* magnetometer data (field directions) between 7 and $20R_E$

There are particles in the magnetosphere which are trapped in Stoermer orbits, namely, the radiation particles which constitute the Van Allen zones. Although it follows that there must be a current associated with these particles, there is evidence which indicates that the radiation particles are not responsible for a current system of sufficient magnitude to account for the geophysical effects attributed to the ring current. First, recent evidence indicates that the radiation particles are high-energy particles (1 Mev) so few in number (much less than 1 cm^{-3}) that their energy density, and total energy, is too small to deform the geomagnetic field substantially (Ref. 45, 46, and 47). Second, observations of the behavior of the outer zone during magnetic storms is contrary to what would be expected if the radiation particles were responsible for the ring current. The high-energy particle count rates decrease during the main phase of the storm and only show large increases during the recovery phase (Ref. 48, 49, and 50). This observation is contrary to the requirements of an enhanced ring current during the main phase which subsequently decays during the recovery phase of the storm.

If the high-energy particle component of the magnetosphere does not cause the ring current, it follows that low-energy plasma might be responsible. If the plasma is of solar origin, it might be anticipated that the kinetic energy of the ions and electrons would correspond to the average velocity of propagation of disturbances from Sun to Earth. A velocity of 1000 km sec^{-1} implies protons of 10 kev average energy and electrons with a kinetic energy of 10 ev. Only two spacecraft so far have contained detectors capable of investigating such low energy protons and electrons. The *Luniks* contained ion traps capable of detecting both ions and electrons with energies above 200 v. *Explorer 10* contained a plasma probe able to detect protons with energies in the range from 5 to 2300 v.

1. Lunik 1 and *2* (Gringauz, Kurt, Moroz, and Shklovsky)

The results of the ion trap measurements can be summarized (Ref. 46):

1. Low-energy plasma was observed out to geocentric distances of 22,000 km. Presumably, this low-energy plasma originates in the Earth's atmosphere at lower levels.

2. No plasma was observed between 22,000 and 55,000 km. The charged particles in this region are predominantly, or entirely, radiation particles. (The propagation of audio frequency electromagnetic radiation through this region of space ("whistlers") implies the presence of very low-energy, thermal plasma, which is not inconsistent with these measurements).

3. Low-energy electrons ($E > 200$ v) were observed in the region from 7 to 13 R_E. Gringauz and Rytov compared these measurements with the parameters of the *Explorer 6 - Pioneer 5* model calculations (Ref. 51). They concluded that the particle characteristics could be reconciled with the characteristics of the ring current suggested by the model calculations. They interpreted the empirical results as indicating the presence of a third particle zone consisting of trapped low energy electrons. The *Pioneer 4* Geiger counter had previously detected particles at the same distances from the Earth (Fig. 12) (Ref. 52). The particle count rate was characterized by persistent, rapid fluctuations. However, measurements with the same equipment on the earlier *Pioneer 3* flight gave no such results (Ref. 53).

2. *Explorer 10* (Bridge, Dilworth, Lazarus, Lyon, Rossi, and Scherb)

The results of these measurements may be summarized (Ref. 54):

1. Low-energy plasma was observed between 1.3 and 2.9 R_E. This observation is consistent with the ion trap measurements above.

2. There was a complete absence of plasma between 2.9 and 21.5 R_E.

3. Plasma was observed intermittently beyond 21.5 R_E.

The absence of plasma beyond 2.9 R_E, and while the *Explorer 10* was inside the geomagnetic field, is an important result. As indicated above, the magnetometer data from *Explorer 10* in the region out to $\sim 10\ R_E$ agrees qualitatively with the *Explorer 6* results. Both magnetometers indicate that the distant geomagnetic field is strongly deformed. The deformation can be visualized as a stretching of the geomagnetic field lines to produce a change in the field magnitude and direction. Since the trajectories of the two spacecraft were similar, it appears likely that the deformation seen by both is characteristic of magnetically quiet periods. The absence of low-energy protons during the *Explorer 10* flight suggests that none was present during the *Explorer 6* measurements. This important conclusion does not, however, rule out the possibility that trapped electrons are responsible for a quiet day ring current or that there may be protons trapped in the magnetosphere during magnetic storms.

D. Evidence Concerning the Existence of the Ring Current: Present Status

The theoretical and experimental aspects of ring currents represent a half century of scientific endeavor. A detailed and well-founded theory has evolved. Although precise details in the application of the theory to the magnetosphere remain to be worked out, ring current theory is one of the major accomplishments of geophysics. Very few theories of geophysical phenomena may represent as close an approximation to an actual geophysical situation. There is indirect evidence for the existence of the ring current based on surface measurements. Rocket technology makes particle and field measurements possible within the region of space where the ring current should exist. The results of the preliminary exploration of the magnetosphere have been described above. In view of these developments, can we, at last, say whether the ring current really exists or not?

The answer is that we still don't know. The following discussion will explore the reasons why we don't know the answer. Such a discussion is valuable because, first, a review of the present status reveals what the remaining obstacles are and suggests how, and when, we can expect a breakthrough, and second, this type of discussion represents an aspect of science which is not normally encountered in textbooks, science as it is practiced rather than science as a body of classified knowledge.

There is sufficient evidence from spacecraft field measurements to establish that the distant geomagnetic field is deformed. At a geocentric distance of 2 to 3 R_E, the *Vanguard 3* and *Explorer 10* data indicate that the geomagnetic field magnitude is depressed by 10 to 100 γ. From 3 to 6 R_E, *Lunik 1* and *Pioneer 5* found $B < G$, while the *Pioneer 1, Lunik 2,* and *Explorer 10* measurements agree with the extrapolated Earth's field in magnitude or radial dependence. Thus, magnetic measurements between 3 and 6 R_E seem to be variable. The apparent inconsistencies could be the result of differences in the spacecraft trajectories and differing magnetic conditions when the measurements were made.

Most of the measurements discussed above were made during relatively quiet magnetic conditions. The *Explorer 6* storm data show a large perturbation of the geomagnetic field at 4 R_E. Thus, we are really considering two closely related problems, the possible existence of a ring current during non-storm as well as storm periods. If the deformation during quiet conditions turns out to have a cause other than a ring current, the question of the the main phase ring current might still be unanswered.

Beyond 6 R_E, the *Explorer 6, Pioneer 5,* and *Explorer 10* magnetometer data all show a deviation between *B* and *G*. A difference in the direction of the observed and extrapolated geomagnetic fields is, perhaps, the most notable feature.

The *Explorer 6* and *Explorer 10* vector field measurements have been transformed into geomagnetic coordinates (radial distance, *R*, geomagnetic latitude δ_M, and longitude, λ_M) and compared (Ref. 54). Figure 26 is the disturbance field in geomagnetic coordinates as measured by *Explorer 6*. The disturbance field, *F*, is equal to $B - G$. *B* is obtained by transforming the measured field parameters $B_\perp$ and ϕ into geomagnetic coordinates, assuming there is no component of *F* perpendicular to the magnetic meridian plane (the plane containing the Earth's dipole field line and the center of the Earth). *F* is shown at several positions on the *Explorer 6* trajectory as viewed from a direction perpendicular to the local magnetic meridian plane. The data were obtained on August 9, 1959 (during a moderately disturbed interval) and were used in conjunction with the model calculations discussed above.

Figure 27 is the corresponding result for the disturbance field measured by *Explorer 10* (during a quiet

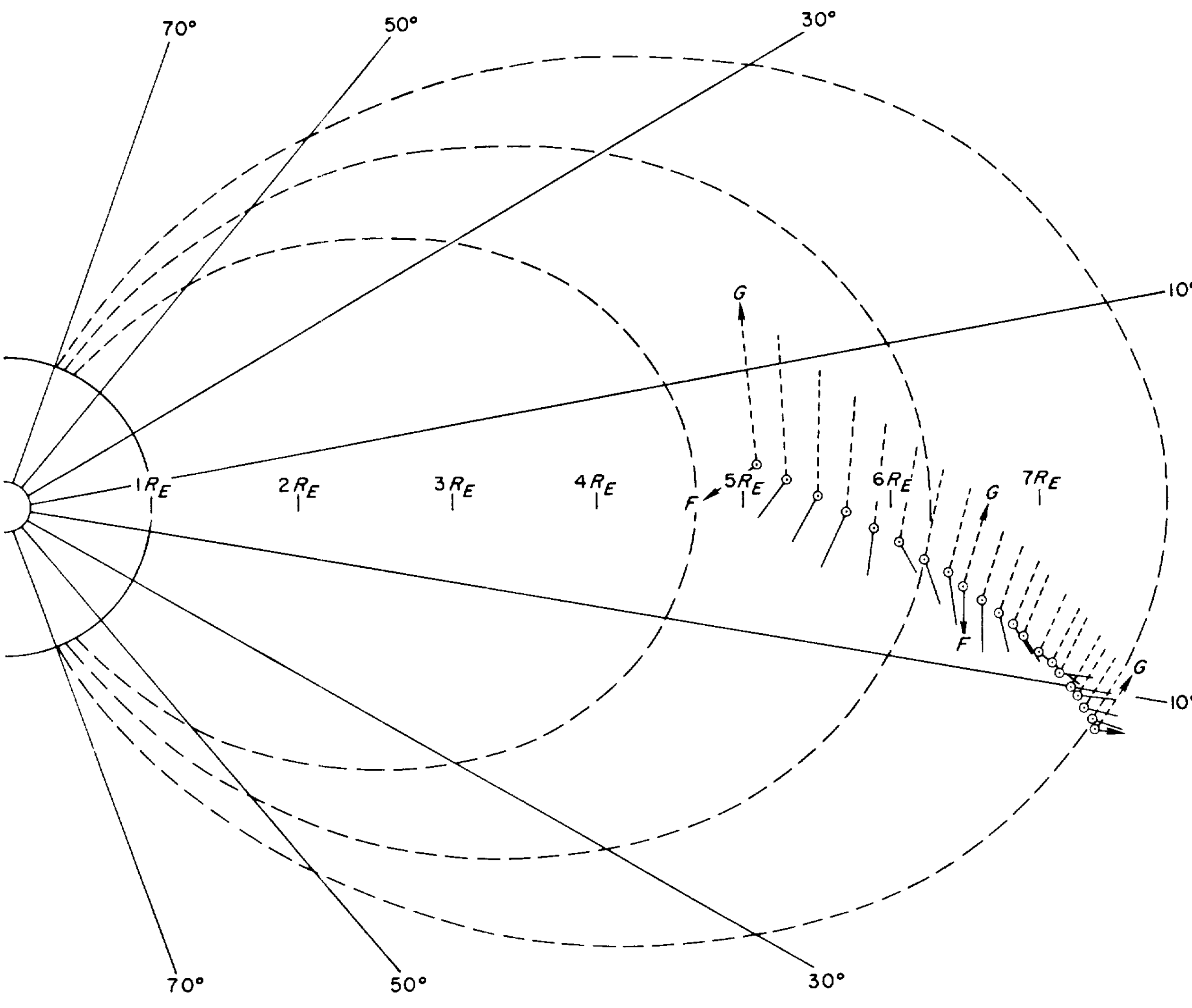

Fig. 26. Disturbance field in geomagnetic coordinates: *Explorer 6*

interval). Figures 26 and 27 show a southward directed disturbance field vector, F, which rotates counterclockwise with increasing radial distance. The qualitative agreement between the two sets of data confirms that a large-scale deformation of the geomagnetic field is present, beyond 6 R_E, even on non-storm days. The disturbance field is such that the dipole field lines are "stretched out" but remain inside magnetic meridian planes.

The fact that the distant geomagnetic field is deformed does not establish the existence of a ring current. Persistent interest in the ring current can probably be explained by (1) the basic simplicity of such a current system and (2) the assumption that most of the geomagnetic field occupied a vacuum. It is difficult to imagine a current system, capable of producing a quasi-uniform field surrounding the Earth, that can be described as simply as a ring current (although the modern ring current is considerably more complicated than the original concept of it). The recognition that both the outer atmosphere and interplanetary space are hydromagnetic media has been a comparatively recent development. The

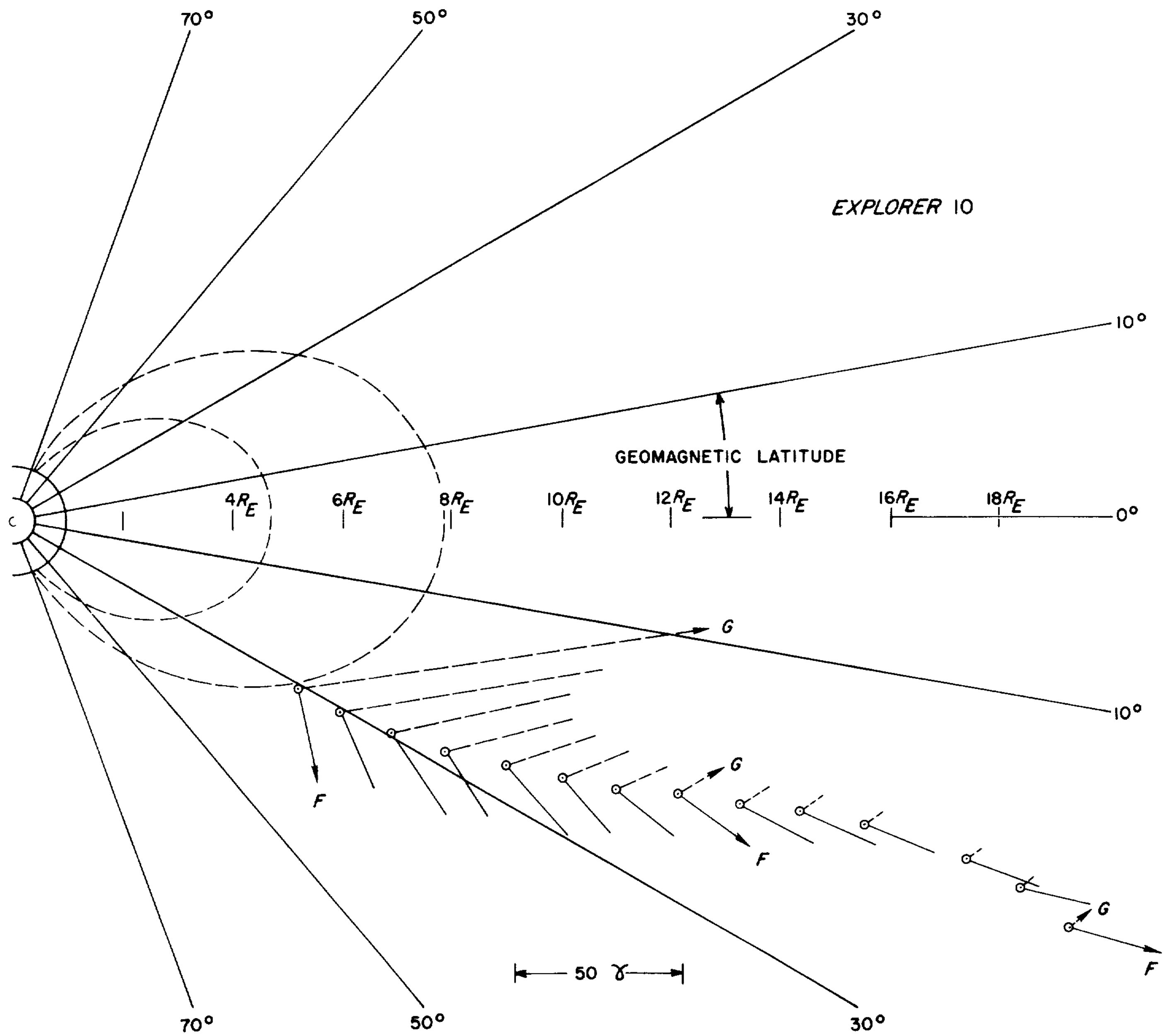

Fig. 27. Disturbance field in geomagnetic coordinates: *Explorer 10*

additional complexity in the composition and dynamics of both provides other possible explanations for a deformation of the geomagnetic field.

One of the most promising alternatives appears to be a theory proposed by Piddington (Ref. 56 and 57). He suggested another mechanism for producing a large-scale reduction of the geomagnetic field, which involves the interaction between the distant geomagnetic field and the streaming solar plasma. In common with many other theorists, he initially adopts the Chapman-Ferraro view, with the Earth's field being confined to a cavity inside the plasma. Small scale irregularities enable geomagnetic field lines to diffuse into the plasma. The field lines, which are embedded in the streaming solar plasma, are transported around to the side of the Earth opposite the sun to form a magnetic "tail" (see Fig. 28). As field lines diffuse outward, the magnitude of the geomagnetic field inside the cavity is reduced, since there are now fewer field lines inside the magnetosphere. Since the magnetosphere contains plasma, and is a hydromagnetic medium, the stresses which are set up could cause a redistribution of the field such that the deformation is symmetric near the Earth (Ref. 58). Thus, according to the theory, the main phase decrease is a characteristic deformation of the magnetosphere caused by solar plasma. This is presumably accomplished without the necessity of trapping plasma in the geomagnetic field. The arguments apply as well to non-storm conditions, the only difference being the kinetic energy density of the solar plasma and the magnitude of the effect in the magnetosphere (Ref. 3).

These two alternatives, the ring current and magnetic tail, are not necessarily mutually exclusive. There appears to be no reason to exclude the simultaneous occurrence of both a magnetic tail and a ring current. If there is unstable equilibrium at the magnetopause between the field energy density and the particle energy density, perhaps both trapping of particles and transport of the geomagnetic field can occur. A recent storm theory due to Axford and Hines deals with the deformed magnetosphere and has plasma being convected into the geomagnetic field from the magnetic tail to cause a storm-time ring current (Ref. 59).

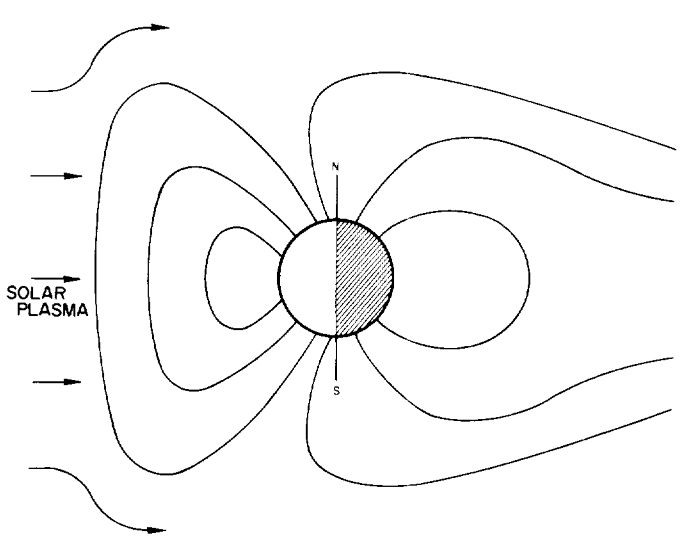

Fig. 28. The deformation of the geomagnetic field by the solar wind

At the present time, we cannot decide between these two alternatives by a comparison between observation and theory. The experimental measurements do not yield a clear-cut description of the deformation, and theoretical calculations involving the ring current cannot be compared with the data in a definitive way. The theoretical calculations have been based on a few, restricted particle distribution functions. This was necessary in order to simplify the mathematics, and because the particles which are presumably responsible for the ring current have not been observed, so their distribution function is unknown. Furthermore, most calculations have been restricted to points of observation on the magnetic equatorial plane. On the other hand, none of the spacecraft orbits were confined to equatorial planes but involved latitude variations. A rudimentary comparison was carried out by Apel, Singer, and Wentworth, using the *Lunik 1* and *Explorer 6* data, and by Akasofu and Chapman, who used the *Explorer 6* data (Ref. 28 and 29). Both these comparisons suffered from the limitations mentioned above. Model currents have also been invoked to see whether or not the data is consistent with the existence of a field caused by a ring current. Such calculations have provided some agreement with the observed field. However, it is not always possible to get satisfactory agreement by using simple models. Furthermore, when agreement has been obtained there were ambiguities associated with the reversal of the Earth's field gradient. Furthermore, it has not been possible to compare the data with the magnetic tail theory, which is completely qualitative at present.

Presumably, simultaneous particle and field observations could resolve this problem. If we knew the particle characteristics and the nature of the field deformation, the ring current theory could establish whether or not the two observations were mutually consistent. Moreover, the presence or absence of trapped particles, with a kinetic energy density large enough to strongly deform the geomagnetic field, is a fundamental distinction between theories involving the ring current and the magnetic tail.

Actually, it has been customary to make simultaneous particle and field measurements on spacecraft. The spacecraft discussed above (Table 1) carried particle detectors as well as magnetometers. However, very simple particle detectors were included and they were intended to investigate the presence of high energy particles. The description of the particles which have been observed, e.g. in the radiation zones, appears to be quite complicated. The data involve ambiguities about the sign of the particles (both protons and electrons appear to be present) and their energies. In any case, the particles responsible for the outer radiation zone apparently do not cause the ring current. The radiation zones seem to be controlled by the field changes rather than the converse. Observations of low energy particles have been attempted (e.g., *Explorer 10*) but they were restricted to a single particle species and a limited energy range.

The situation at the present time may be summarized as follows. Although we have learned a great deal from experimental space science, we still do not possess much of the basic knowledge about the magnetosphere. In order to settle the question of the existence of the ring current, we will need more, and better, experimental data. What is required are (1) simultaneous field and particle measurements in which particles of both signs and all energies are differentiated, (2) a better understanding of the extent of the magnetosphere and its shape, and (3) theoretical calculations which are less restricted and which apply more nearly to the actual measurements. This seems to imply a future effort of considerable magnitude. Of course, there is an element of chance involved and we could be lucky enough to settle this question in the near future with measurements carried out on a single spacecraft. Irrespective of how and when the problem of the geomagnetic ring current is finally resolved, knowledge of the theoretical and experimental aspects of ring currents discussed above will be required in order to understand and appreciate the answer.

REFERENCES

1. J. W. Dungey, *Cosmic Electrodynamics,* Cambridge University Press, Cambridge (1958).
2. D. B. Beard, *Journal of Geophysical Research 65,* 3559 (1960).
3. F. S. Johnson, *Journal of Geophysical Research 65,* 3049 (1960).
4. S. Chapman and Bartels, J., *Geomagnetism,* Vol. 1 and 2, Oxford University Press, New York (1949).
5. C. Stoermer, *The Polar Aurora,* Clarendon Press, Oxford (1955).
6. R. C. Bless, Gartlein, C. W., Kimball, D. S., and Sprague, G., *Journal of Geophysical Research 64,* 949 (1959).
7. P. J. Kellogg and Winckler, J. R., *Journal of Geophysical Research 66,* 3991 (1961).
8. E. H. Vestine, in *Physics of the Upper Atmosphere,* ed. by J. A. Ratcliffe, Academic Press, New York (1960), p. 471.
9. A. Schmidt, *Abh. der Kgl. Pr. Met. Inst. 5,* 37 (1916), also *Encyclopedia der Math. Wiss. 6,* 334.
10. S. Chapman, and Ferraro, V. C. A., *Terr. Magn. 36,* 77, 171 (1931), *Terr. Magn. 37,* 147, 421 (1932), *Terr. Magn. 38,* 79 (1933), *Terr. Magn. 45,* 245 (1940), *Terr. Magn. 46,* 1 (1941).
11. H. Alfvén, *Tellus* 7, 50 (1955).
12. H. Alfvén, *Cosmical Electrodynamics,* Clarendon Press, Oxford (1950).
13. W. K. H. Panofsky and Phillips, M., *Classical Electricity and Magnetism,* Addison-Wesley Publishing Company, Reading, (1955), p. 149.
14. A. Behr, Siedentopf, H., and Elsasser, H., *Nature 171,* 1066 (1953).
15. D. E. Blackwell, *Observatory 77,* 187 (1957).
16. L. R. O. Storey, *Philosophical Transactions of the Royal Society* (London) A *246,* 113 (1953).
17. L. Biermann, *Observatory 77,* 109 (1957).
18. E. N. Parker, in *Plasma Physics,* ed. F. H. Clauser, Addison-Wesley Publishing Company, Reading, (1960), p. 233.
19. T. Gold, in *Dynamics of Cosmic Clouds,* J. M. Burgers and H. C. Van de Hulst, eds., Interscience Publishers, New York (1955), p. 103.
20. S. F. Singer, *Transactions of the American Geophysical Union 38,* 175 (1957).
21. E. N. Parker, *Astrophysics,* J *129,* 217 (1959).
22. A. J. Dessler, and Parker, E. N., *Journal of Geophysical Research 64,* 2239 (1959).
23. C. P. Sonett, *Journal of Geophysical Research,* to be published (1962).
24. S. F. Singer, *Physical Review* Letter *1,* 171 (1958). Also S. F. Singer and A. M. Lenchek, "Geomagnetically Trapped Radiation," in *Progress in Cosmic Ray Physics,* Vol. 6, Interscience, New York (1962).
25. P. J. Kellogg, Nuovo Cimento *11,* 48 (1959).
26. W. Hess, *Physical Review* Letter 3, 11 (1959).
27. S. Chandrasekhar, *Plasma Physics,* ed. S. K. Trehan, University of Chicago Press, Chicago (1960).
28. S. I. Akasofu and Chapman, S., *Journal of Geophysical Research 66,* 1321 (1961).
29. J. Apel, Singer, S. F., and Wentworth, R. C., *Advances in Geophysics,* eds. H. E. Landsberg and J. V. Mieghem, Vol. IX, Academic Press, New York (1962).
30. S. K. Mitra, *The Upper Atmosphere,* The Asiatic Society, Calcutta (1952).
31. E. C. Ray, *Physical Review 101,* 1142 (1956).
32. C. P. Sonett, Judge, D. L., Sims, A. R., and Kelso, J. M., *Journal of Geophysical Research 65,* 55 (1960).
33. S. Dolganov, and Pushkov, N., Doklady, Academy of Sciences AN-SSSR *129,* 1 (1959).
34. M. G. Antsilevich, and Shevnin, A. D., DOKL, AN-SSSR *135,* 298 (1960).
35. J. R. Apel, Masters Thesis, University of Maryland (1960).
36. V. I. Krassovsky, *Astronautica Acta. 6,* 32 (1960).
37. C. P. Sonett, Smith, E. J., Judge, D. L., and Coleman, P. J., *Physical Review* Letter *4,* 161 (1960).

REFERENCES (Cont)

38. C. P. Sonett, Smith, E. J., and Sims, A. R., *Space Research,* Proceedings of First International Space Science Symposium, ed. H. Kallman Bijl, North Holland Publishing Company, Amsterdam, (1960), p. 982.

39. E. J. Smith, Coleman, P. J., Judge, D. L., and Sonett, C. P., *Journal of Geophysical Research 65,* 1858 (1960).

40. E. J. Smith, and Sonett, C. P., Proceeding of International Conference on Cosmic Rays and the Earth Storm (Kyoto, September 1961), to be published (1962).

41. R. L. Arnoldy, Hoffman, R. A., and Winckler, J. R., *Journal of Geophysical Research 65,* 3004 (1960).

42. A. Rosen, Farley, T. A., and Sonett, C. P., *Space Research,* ed. by H. Kallman Bijl, North Holland Publishing Company, Amsterdam, (1960), p. 938.

43. J. P. Heppner, Stolarik, J. D., Shapiro, I. R., and Cain, J. C., *Space Research,* ed. by H. Kallman Bijl, North Holland Publishing Company, Amsterdam, (1960), p. 982.

44. J. P. Heppner, Ness, N. F., Skillman, T. L., and Scearce, C. S., Proceedings of International Conference on Cosmic Rays and the Earth Storm (Kyoto, September 1961), to be published (1962).

45. A. Rosen, and Farley, T. A., *Journal of Geophysical Research 66,* 2013 (1961).

46. K. I. Gringauz, Kurt, V. G., Moroz, V. I., and Shklovskii, I. S., *Astronomical Journal* (Academy of Sciences of USSR) *37,* (1960).

47. B. J. O'Brien, Van Allen, J. A., Laughlin, C. D., and Frank, L. A., *Journal of Geophysical Research 67,* 397 (1962).

48. R. Arnoldy, Hoffman, R., and Winckler, J. R., *Space Research,* ed. H. Kallman Bijl, North Holland Publishing Company, Amsterdam, (1960), p. 877.

49. E. Y. Fan, Meyer, P., and Simpson, J. A., *Space Research,* ed. H. Kallman Bijl, North Holland Publishing Company, Amsterdam, p. 951 (1960).

50. P. Rothwell, and McIlwain, C. E., *Space Research,* ed. H. Kallman Bijl, North Holland Publishing Company, Amsterdam (1960), p. 897.

51. K. I. Gringauz, and Rytov, S. M., DOKL, AN-SSSR *135,* 48 (1960).

52. J. A. Van Allen, and Frank, L. A., *Nature 184,* 219 (1959).

53. J. A. Van Allen, and Frank, L. A., *Nature 183,* 430 (1959).

54. H. S. Bridge, Dilworth, C., Lazarus, A., Lyon, E. F., Rossi, B., and Scherb, F., Proceedings of International Conference on Cosmic Rays and the Earth Storm (Kyoto, September 1961), to be published (1962).

55. E. J. Smith, *Journal of Geophysical Research,* to be published (1962).

56. J. H. Piddington, *Geophysical Journal 2,* 173 (1959).

57. J. H. Piddington, *Journal of Geophysical Research 65,* 93 (1960).

58. E. N. Parker, *Physics of Fluids 1,* 171 (1958).

59. W. I. Axford, and Hines, C. O., *Canadian Journal of Physics 39,* 1433 (1961).